8.0 QUANTIFICATION OF NET WATER LOSSES TO SALTON SEA AND ADJACENT WETLANDS

8.0 QUANTIFICATION OF NET WATER LOSSES TO SALTON SEA AND ADJACENT WETLANDS

8.1 CONCEPTUAL MODEL WATER BALANCE ESTIMATES

8.1.1 Groundwater Discharge to Wetlands

Sections 3, 4, and 5 present a conceptual model of the groundwater consumption rates during the late 1980s for wetlands associated with the canals. Groundwater consumptive use rates from all canal wetlands complexes are summarized in Table 8-1. Groundwater consumptive use rates for the AAC wetlands are 7,429 acre-feet per year prior to lining and 7,159 acre-feet per year after lining and the implementation of mitigation measures. The net change is a decrease of 270 acre-feet per year due to the combination of lost canal bank vegetation and desert riparian wetlands (between Drops 2 and 3) and a gain in marsh/desert riparian wetlands due to mitigation measures applied at the Drop 3/Drop 4 complex. Although the mitigation measure results in a small net loss in seepage used by wetlands, there is no net loss in habitat value because the mitigation measure at the Drop 3/Drop4 complex replaces the poorer quality desert riparian wetland (50% salt cedar) between Drop 2 and 3 with higher quality marsh/desert riparian wetland.

Table 8-1

AAC and CB Wetland Groundwater Consumption
Conceptual Model of Pre- and Post-Lining Conditions

Wetland Complex	Wetland type	Current water use (af/yr)	Post-lining wetland water use (af/yr)	Change in water use (af/yr)	Percent Change
AAC-Drop 3/4	Marsh and desert riparian (9% marsh)	6,941	7,159	218	3.14
AAC-Drop 2/3 scattered	Desert riparian	488		-488	-100.00
AAC-canal bank	Marsh	240		-240	-100.00
Total AAC		**7,429**	**7,159**	**-270**	**-3.63**
CB- Unit A	Desert riparian (0.1% marsh)	3,510	1,930	-1,580	-45.01
CB- Unit B	Desert riparian (1.2% marsh)	2,675	82	-2,593	-96.93
CB- Unit C	Desert riparian (0.9% marsh)	11,100	0	-11,100	-100.00
CB- Unit D	Marsh and desert riparian (6% marsh)	20,340	14,181	-6,159	-30.28
CB- Unit E	Desert riparian (1.7% marsh)	385	57	-328	-85.19
Total CB		**38,010**	**16,250**	**-21,760**	**-57.25**
Total AAC and CB		**45,439**	**23,409**	**-22,030**	**-48.48**

Groundwater consumptive use rates for the CB wetlands are 38,010 acre-feet per year prior to lining and 16,250 acre-feet per year after lining and the implementation of mitigation measures. The net change is a decrease in seepage flux of 21,760 acre-feet per year due the loss of nearly all salt cedar, salt cedar/mixed vegetation, and other desert riparian in hydrologic units B, C, and E; the loss of 45 percent of vegetation in hydrologic unit A; and the loss of 30 percent of the marsh, salt cedar, salt cedar/mixed vegetation in hydrologic unit D (unit D includes the Salt Creek ACEC). The net loss of 30 percent of the marsh/desert riparian habitat in hydrologic unit D (6,159 acre-feet per year of seepage) reflects a loss of 13,284 acre-feet per year in seepage due to lining which is offset by an increase of 7,125 acre-feet per year for water supply for new wetlands created in Salt Creek. Although the mitigation measures still result in a 57 percent net loss in seepage used by wetlands, there is no net loss in habitat value because the mitigation measures replace the poorer quality desert riparian wetland (mostly salt cedar) with higher quality marsh/wetland (i.e., native cottonwood/willow, fan palms, honey mesquite, and screwbean mesquite).

8.1.2 Groundwater Discharge to Surface Waters

Sections 3, 4, and 5 present a conceptual model of groundwater discharge rates during the late 1980s to surface waters that drain into the Salton Sea. Some fraction of this groundwater discharge may be comprised of water derived from canal seepage. Groundwater discharge rates to major surface waters such as the East Highline Canal, the New and Alamo Rivers, the IID Drains, the Salton Sea, and Salt Creek are summarized in Table 8-2.

AAC canal seepage may contribute groundwater discharge into the East Highline Canal, the New and Alamo Rivers, the IID Drains, and the Salton Sea. It has been estimated that approximately 8,900 acre-feet per year of AAC seepage flows north towards Imperial Valley, and lining the canal to Drop 3 will decrease this seepage flow into Imperial Valley to the approximately 1,500 acre-feet per year of seepage between Drop 3 and the EHC. A large fraction (4,400 acre-feet per year) of groundwater discharge into the East Highline Canal is attributed to AAC seepage, therefore, there may be a significant reduction in groundwater discharge into the East Highline Canal after lining the AAC. But, because there is no direct or indirect pathway for the EHC water to the Salton Sea (see Section 4.4.4.1), lining the canal will not result in a net change in seepage water reaching the Salton Sea. The amount of groundwater that currently underflows the EHC is 4,900 acre-feet per year and after lining the canal this underflow rate is likely to drop to between 0 and 1,500 acre-feet per year, for a net reduction in seepage of 3,500 to 4,900 acre-feet per year. An unknown fraction of this canal seepage may reach the Salton Sea.

Table 8-2

Surface Water Groundwater Discharge for AAC and CB Conceptual Model of Pre- and Post-Lining Conditions

Surface Water Feature	Pathway to Salton Sea	Current Groundwater Discharge (af/yr)	Post-lining Groundwater Discharge (af/yr)
East Highline Canal	none	4,400	unknown
New River	direct discharge of fraction not consumed by ET	29,000	unknown
Alamo River	direct discharge of fraction not consumed by ET	60,400	unknown
IID Drains (south)	discharge via rivers of fraction not consumed by ET	NA - covered in New and Alamo River above	unknown
IID Drains (north of Vail Lateral)	direct discharge of fraction not consumed by ET	10,200	unknown
Salton Sea (SS)	direct discharge	2,000	unknown
Total surface water discharge to Salton Sea (AAC)	direct discharge of fraction not consumed by ET	104,200	unknown
Total groundwater discharge to Salton Sea (AAC)	direct discharge	2,000	unknown
Total water discharge to Salton Sea (AAC)		106,200	unknown
Salt Creek	direct discharge of fraction not consumed by ET	2,000	unknown
Salton Sea	direct discharge	8,000	unknown
Total surface water discharge to Salton Sea (CB)	direct discharge of fraction not consumed by ET	2,000	unknown
Total ground water discharge to Salton Sea (CB)	direct discharge	8,000	unknown
Total water discharge to Salton Sea (CB)		10,000	unknown
Total surface water discharge to Salton Sea (AAC+CB)	direct discharge of fraction not consumed by ET	106,200	unknown
Total groundwater discharge to Salton Sea (AAC+CB)	direct discharge	10,000	unknown
Total water discharge to Salton Sea (AAC+CB)		116,200	unknown

Total groundwater discharge rates into the New and Alamo Rivers, the IID Drains, and into Salton Sea are given in Table 8-2. However, it is difficult to estimate what fraction of these groundwater discharge rates represent groundwater derived from canal seepage due to the large distance and travel time between the canals and the discharge points, and a large number of assumptions would need to be made to make qualitative calculations (see discussion in Appendix D). For this reason, the values given by the groundwater model are thought to be much more accurate and no qualitative estimates were derived for the fraction of canal water in groundwater seepage into the New and Alamo Rivers, the IID Drains, and into Salton Sea.

CB canal seepage may contribute groundwater discharge into the Salton Sea and Salt Creek. It has been estimated that 8,000 acre-feet per year of groundwater discharges from the East Salton Sea area into the Salton Sea and 2,000 acre-feet per year of groundwater discharges from the East Salton Sea area into Salt Creek. Without mitigation measures, the Salt Creek baseflow would naturally cease after lining the canal since there was no baseflow prior to the CB. However, groundwater discharge into Salt Creek will remain the same after lining the CB based on a mitigation commitment to maintain 2,000 acre-feet per year of baseflow in Salt Creek. Currently, 29,810 acre-feet per year of the CB canal seepage is consumed as wetland evapotranspiration and 1,000 acre-feet per year of the CB canal seepage discharges into Salt Creek, allowing up to 1,540 acre-feet of canal seepage to potentially discharge into the Salton Sea. However, given that (1) canal seepage is not detected in the downgradient Andreas and Oasis Springs, (2) the San Andreas Fault may prevent a barrier to migration, and (3) the 1,540 acre-feet per year could be attributed to the range of uncertainty in the amount of canal water estimated to discharge into Salt Creek and the wetlands, it seems possible that canal seepage does not discharge into the Salton Sea. If this is the case, anywhere from 0 to 1,500 acre-feet per year of canal water may be lost as seepage into the Salton Sea.

8.2 NUMERICAL MODEL ESTIMATES

8.2.1 Groundwater Discharge to Wetlands

Sections 6 and 7 presents a numerical model that quantifies the groundwater budget including canal seepage and wetland groundwater consumption. The model calculates a quantitative water budget for the conditions with and without the canal-lining project as given in Figures 7-2 through 7-5. Water use rates from canal wetlands are summarized in Table 8-3. The water use rate for the AAC wetlands is

5,546 acre-feet per year after lining and the implementation of mitigation measures. The change is due to: (1) a combination of lost canal bank vegetation and desert riparian wetlands between Drops 2 and 3 (120 and 500 af/yr, respectively); (2) a gain in marsh/desert riparian wetlands due to mitigation measures applied at the Drop 3/Drop 4 complex (1,187 to 2,993, plus 220 af/yr, as described in Section 7.2.3.2); and (3) a decrease in groundwater evapotranspiration (ranging from 1,187 to 2,993 af/yr). Although the mitigation measure results in a small net loss in seepage used by wetlands, there is no net loss in habitat value because the mitigation measure replaces the poorer quality desert riparian wetlands (50% salt cedar) between Drops 2 and 3 with higher quality marsh/desert riparian wetland between Drops 3 and 4

Table 8-3

**AAC and CB Wetland Water Use,
Numerical Model of Lined and Unlined Conditions in 2026
(with mitigation)**

Wetland Complex	Wetland Type	Unlined Water Use* (af/yr)	Lined Water Use* (af/yr)		Change in Water Use* (af/yr)	
			High	Low	High	Low
AAC-Drop3/4	marsh and desert riparian (9% marsh)	5,326	5,546	5,546	+220	+220
AAC-Drop 2/3 scattered	desert riparian	500	0		-500	-500
AAC-canal bank	marsh	120	0		-120	-120
Total AAC		5,946	5,546	5,546	-400	-400
Total CB	marsh and desert riparian (3.8% marsh)	37,941	24,643	14,218	-13,298	-23,723
Total AAC and CB		43,887	30,189	19,764	-13,698	-24,123

Note: *Model output values are rounded only to the nearest af/yr for convenience in verifying against model output files. Rounding to the nearest 1.000 af/yr is appropriate to indicate the degree of predictive accuracy.

Uncertainty in the predictions of lined water use rates for 2026 is quantified in Table 8-3 by showing the high and low ends of the predicted range for each rate. These values are the same for the AAC, due to the effects of mitigation measures.

Groundwater consumptive use rates for the CB wetlands in 2026 are 37,941 acre-feet per year without lining and range between 14,218 to 24,643 acre-feet per year with lining and the implementation of mitigation measures. Again, there is no net loss in habitat value because the mitigation measure replaces the poorer quality desert riparian wetlands (70% salt cedar) with higher quality native marsh, honey mesquite, and screwbean mesquite.

8.2.2 Groundwater Discharge to Surface Waters

Sections 6 and 7 presents a numerical model which quantifies the groundwater budget, including the relation between canal seepage and groundwater discharge rates to surface waters that drain into the Salton Sea. Groundwater discharge rates to major surface water features which contribute flow to the Salton Sea, including the New and Alamo Rivers, the IID drains, the Salton Sea itself, and Salt Creek, are summarized in Table 8-4. Uncertainty in the predictions of lined discharge rates for 2026 is quantified in Table 8-4 by showing the high and low ends of the predicted range for each rate.

Table 8-4

Groundwater Discharge to Surface Water Features, Numerical Model of Lined and Unlined Conditions in 2026 (with mitigation)

Surface Water Feature	Pathway to Salton Sea	Unlined Groundwater Discharge [1] (af/yr)	Lined Groundwater Discharge [1] (af/yr)		Change In Groundwater Discharge [1] (af/yr)	
			High	Low	High	Low
New River and Alamo River	Direct discharge of fraction not consumed by ET	63,324	63,315	63,210	-9	-114
IID Drains	Discharge via rivers of fraction not consumed by ET	21,769	20,798	9,227	-971	-12,542
Salton Sea (SS)	Direct discharge	24,320	22,605	14,112	-1,715	-10,208
Salt Creek	Direct discharge of fraction not consumed by ET	2,000	2,000	2,000	0	0
Total surface water discharge		87,093	86,113	74,437	-980	-12,656
Total groundwater discharge	Direct discharge	24,320	22,605	14,112	-1,715	-10,208
Total water discharge to SS	Direct discharge of fraction not consumed by ET	111,413	108,718	88,549	-2,695	-22,864

Note: [1] Model output values are rounded only to the nearest af/yr for convenience in verifying against model output files. Rounding to the nearest 1,000 af/yr is appropriate to indicate the degree of predictive accuracy.

8.3 QUANTIFIED NET WATER LOSSES TO SALTON SEA AND ADJACENT WETLANDS

8.3.1 Comparison of Numerical and Conceptual Model Predictions

The change in seepage rates at the wetlands and Salton Sea due to the AAC and CB canal lining projects is estimated using both the conceptual and numerical models in Table 8-5. The estimated change in seepage rates at the AAC and CB wetlands are quite similar for both calculation methods. This is attributed to greater certainty in the fate of the wetland seepage since the travel times and distances are smaller. In contrast, the estimated change in seepage rates at the Salton Sea covers a much wider range. This is attributed to greater uncertainty in the seepage fate at the Salton Sea since the travel times and distances are so great, especially for the AAC seepage. The conceptual model approach also does not have the ability to track seepage once it enters the complex discharge conditions in central Imperial Valley, while the numerical model can estimate whether seepage discharges into the Salton Sea or into a river or drain feeding the sea.

Table 8-5

Summary of Water Loss Estimates for Conceptual and Numerical Model in 2026

Project	Loss to the Salton Sea acre-feet per year			Loss to the wetlands acre-feet per year		
	Conceptual Model	Numerical Model High	Numerical Model Low	Conceptual Model	Numerical Model High	Numerical Model Low
Total AAC Lining and CB Lining	NA	-3,000	-23,000	-22,000	-14,000	-24,000

Note: Figures have been rounded to the nearest 1,000 acre-feet to reflect the uncertainty in the model predictions

The numerical and conceptual models estimate that the largest change in AAC seepage discharge is for seepage into the East Highline Canal. The numerical model estimates that the second largest change in AAC seepage discharge is for seepage into the IID drains. Thus, a key factor in determining the net seepage loss to the Salton Sea is the fraction of discharge into the IID drains consumed during transport through the drain system; yet, this value is unknown. For this report, none of the surface water discharge was assumed to be consumed during transport to the Salton Sea; thus, these estimates present a worst-case scenario.

The conceptual model estimates a higher loss to wetland but this assumes steady-state conditions. Thus, the numerical model results are more reliable since steady-state conditions may not occur by 2026.

8.4 CONCLUSIONS

8.4.1 Most Likely Estimates

Reviewing the model results, the most likely estimate for the amount of water that may be lost to the Salton Sea and to the adjacent wetlands due to the proposed canal lining projects is 10,000 acre-feet per year and 19,000 acre-feet per year, respectively, for a total of 29,000 acre-feet per year. These estimates account for the mitigation commitments already identified for each project. Specifically, the mitigation commitments take into account current wetlands that are dominated by an invasive exotic phreatophyte--salt cedar. Salt cedar has taken over approximately 50 percent of total wetland acreage in the AAC and 70 percent for the CB. Mitigation measures include the replacement of the poorer quality desert riparian wetlands with higher quality native marsh, honey mesquite, and screwbean mesquite.

8.4.2 Uncertainty in Estimates

There is a much wider range in the predicted seepage losses to the Salton Sea, as compared to the wetlands, due to the greater uncertainty in this estimate as discussed below.

The unlined rates in Tables 8-3 and 8-4 (2026) are subtracted from the high and low lined rates to compute changes in rates (losses) due to lining the canals. "High" unlined rates are used for both calculations, thus the "low" rate changes are probably exaggerated. For example, the "low" value of -23,000 for the loss the Salton Sea may be beyond the actual lower limit. For this reason, we estimated the most likely value (10,000 af/yr) to be near the high end of the computed range (-3,000 to -23,000 af/yr).

The predictions of groundwater loss to the Salton Sea are most sensitive to this, because the Salton Sea may be farther from steady-state in 2026 as compared to the wetlands. The stated range of uncertainty for the wetlands of -14,000 to -24,000 af/yr does not require adjustment.

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APPENDIX A GROUNDWATER MODEL DOCUMENTATION

APPENDIX A

GROUNDWATER MODEL DOCUMENTATION

A.1 BACKGROUND AND THEORY

The three-dimensional movement of groundwater through a porous aquifer under constant density conditions is described using the following partial-differential equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}$$

where

K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are parallel to the major axes of hydraulic conductivity (L/t);
h is the potentiometric head (L);
W is a volumetric flux per unit volume and represents sources/sinks of water (t^{-1});
S_s is the specific storage of the porous material (L^{-1}); and
t is time (t).

For a complete derivation of the above equation and a detailed theoretical summary of the MODFLOW model see McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). The SSA groundwater model developed for this study uses MODFLOW96 (Harbaugh and McDonald, 1996), supplemented with a lake package to simulate the aquifer interaction with the Salton Sea. The lake package theory is included in Section A.4.

A.2 COMPUTER IMPLEMENTATION

The mathematical equation given above is solved using finite-difference techniques and implemented in a computer program. Documentation of the computer program and a users manual can be found in McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). Documentation of the computer program and a users manual for the lake package is included in Section A.4. Documentation, a users manual, and copies of the model MODFLOW96 can be downloaded free of charge from the Internet at the following USGS address: http://water.usgs.gov/software/modflow-96.html. A USGS Summary of MODFLOW is also included in Section A.4

A.3 SSA SEEPAGE MODEL CALIBRATION

This section presents additional figures and tables documenting the groundwater calibration, including plots of simulated and measured water levels and an analysis of the model error, which were only briefly summarized in the main body of the report.

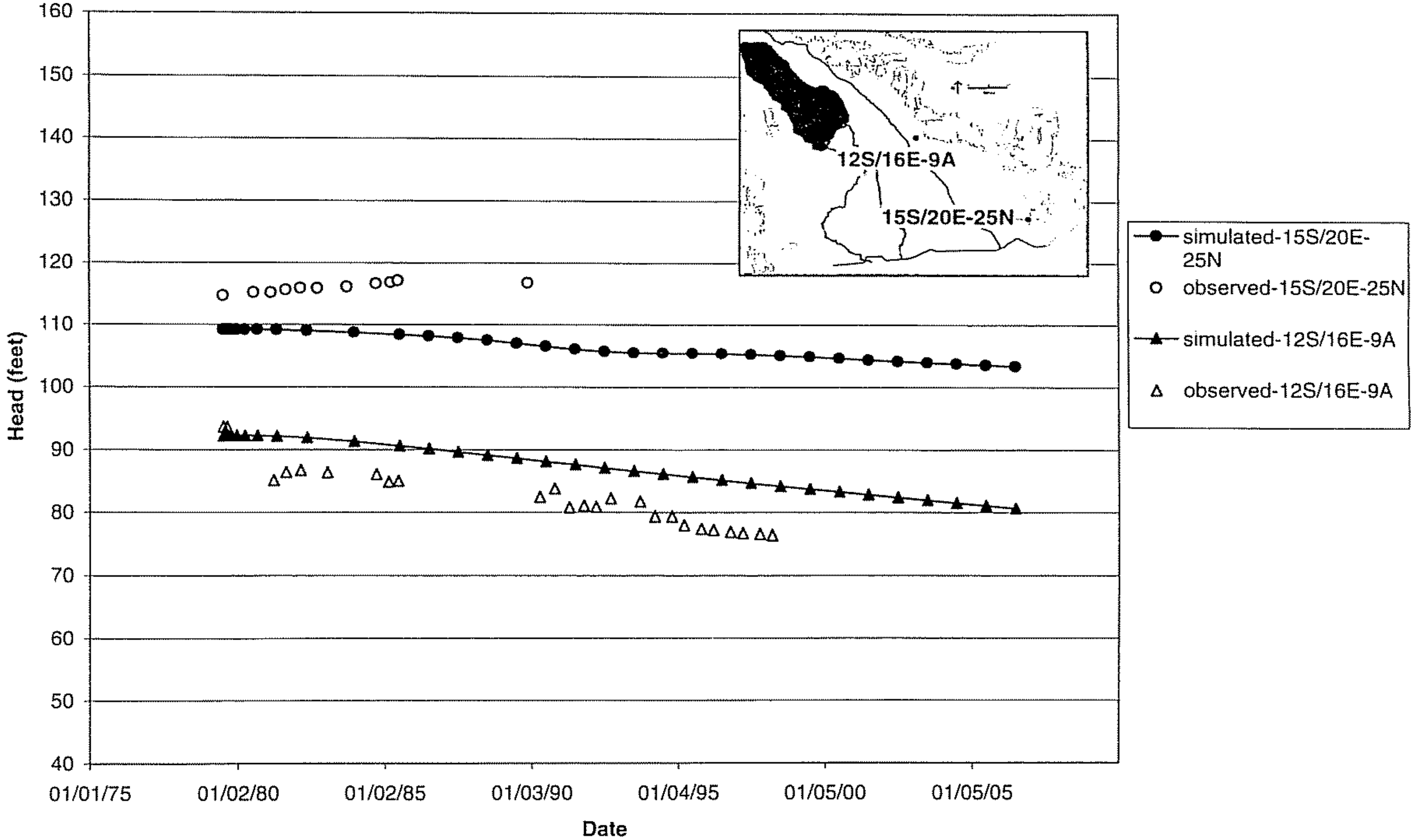

Figure A-1. Hydrographs showing Simulated and Observed Water Levels in Wells 15S20E25N and 12S16E9A

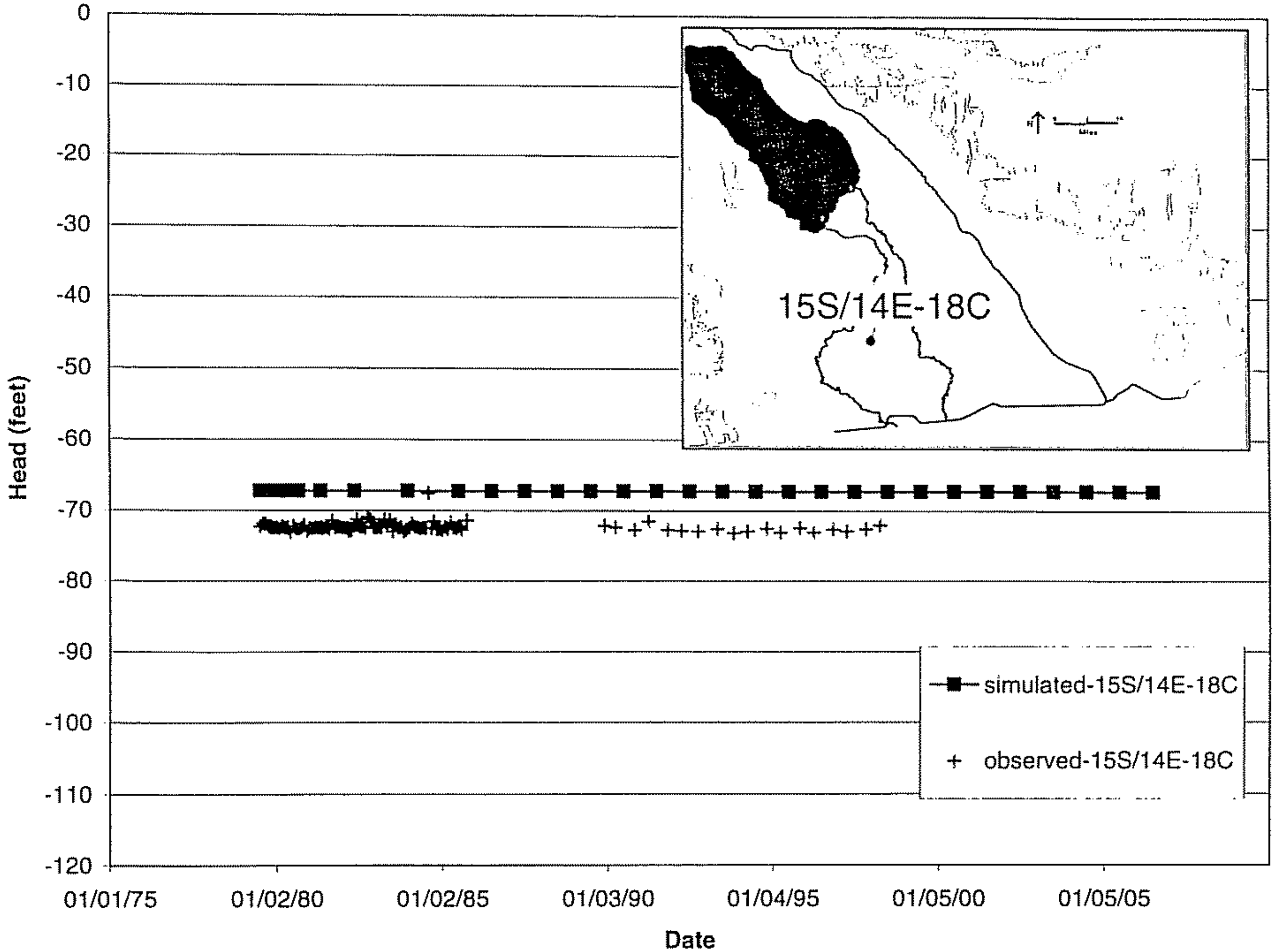

Figure A-2 . Hydrographs showing Simulated and Observed Water Levels in Well 15S14E18C

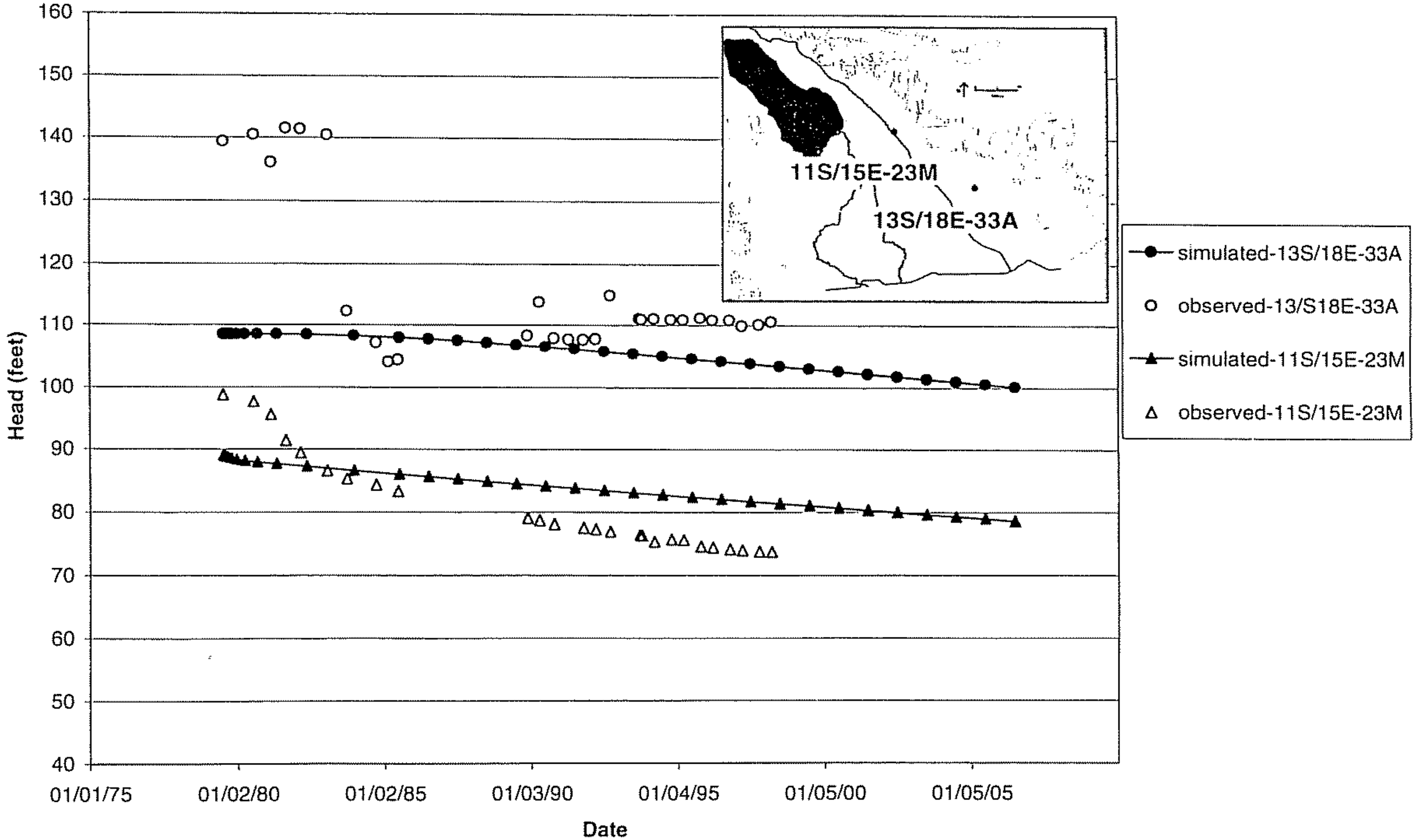

Figure A-3 . Hydrographs showing Simulated and Observed Water Levels in Wells 13S/18E-33A and 11S/15E-23M

A.4 SSA SEEPAGE MODEL SUPPORTING DOCUMENTATION

Section A.4.1 provides supporting documentation on the theory of the MODFLOW lake package. Section A.4.2 provides supporting documentation for the MODFLOW lake package users manual. See also Appendix B for model execution instructions. Section A.4.3 provides a USGS summary of MODFLOW, including an extensive reference list and historical overview of the model development.

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Section A.4.1

A Lake Package for MODFLOW

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A Lake Package for MODFLOW

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ABSTRACT

A new package was developed for simulating lake-groundwater interaction with MODFLOW. This Lake package calculates lake level fluctuations resulting from simulated environmental stresses. Four simulation modes are provided: 1) steady-state mode to compute the lake stage in equilibrium with ground-water head, 2) transient mode to compute stage as a function of time, 3) specified-stage mode with the stage held constant during stress periods, and 4) specified-stage mode with stage varying linearly during stress periods. The Lake package is also linked to the Streamflow Routing package to simulate lake-stream interaction. General equations of stream outflow as a function of lake stage are used. This Lake package provides a broader range of features than previously-documented lake and reservoir packages.

The Lake package is effective because it allows a MODFLOW user to treat lake stage as an unknown variable, it adjusts a lake's area (the number of wetted cells) and flow budget as the stage changes, and it automatically updates the flow into connected streams. With the Lake package, a single model can be used to predict the effect of a groundwater stress (e.g. a pumping well or mine) on aquifer heads and nearby lake levels.

The package has been applied at a proposed underground mine site in northern Wisconsin. Transient and steady-state simulations were used to predict lake level decline at four lakes in response to mine operation.

INTRODUCTION

Numerical models of groundwater and surface water flow help us understand environmental systems, identify the important parameters affecting flow, and predict responses to various types of development (e.g. drilling a well to remove groundwater from an aquifer, installing a control structure on a lake, or dewatering the underground workings of a mine). Traditionally, separate models have been used to analyze surface water and groundwater resources. However, it is often important to recognize that the interaction between surface water and groundwater requires a model that incorporates both components. A change in groundwater head can affect the water level in overlying lakes and vice-versa, because of flow through permeable lakebeds. The surface water and groundwater systems are thus coupled, and a model that analyzes both systems simultaneously is often desirable.

Figure 1 depicts a lake and its volumetric budget components. The various inflows and outflows are used to determine the stage (water elevation) of the lake. In order to properly model the lake, all of the volumetric components must be accounted for. In many applications, many of the lake budget components will vary as the (potentially unknown) lake stage changes. The Lake package for MODFLOW (LAK2 Version 2.2) handles the lake-groundwater and lake-stream interactions including allowances for lake expansion and contraction, multiple inflow and outflow streams, and user-specified stage-outflow relationships. The user can choose to have the model calculate the steady-state or transient lake stage, or the stage can be specified as a linear function of time.

The Lake package was developed as part of a broad study of the environmental effects of a proposed mine in Northern Wisconsin (Foth & Van Dyke, 1995). As part of the regulatory permitting process, a MODFLOW model was developed to determine the effect of proposed mining on groundwater and surface water in the vicinity of the mine. Using the Lake package, the model predicts the amount of decline in lake stage at four lakes of interest at the site. That study demonstrates the package's utility and is discussed in greater detail later in this paper.

DEVELOPMENT HISTORY

MODFLOW and Standard Packages

The MODFLOW program solves (via iterative approximations) the groundwater flow equation, which is a combination of the continuity equation and Darcy's Law:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} \tag{1}$$

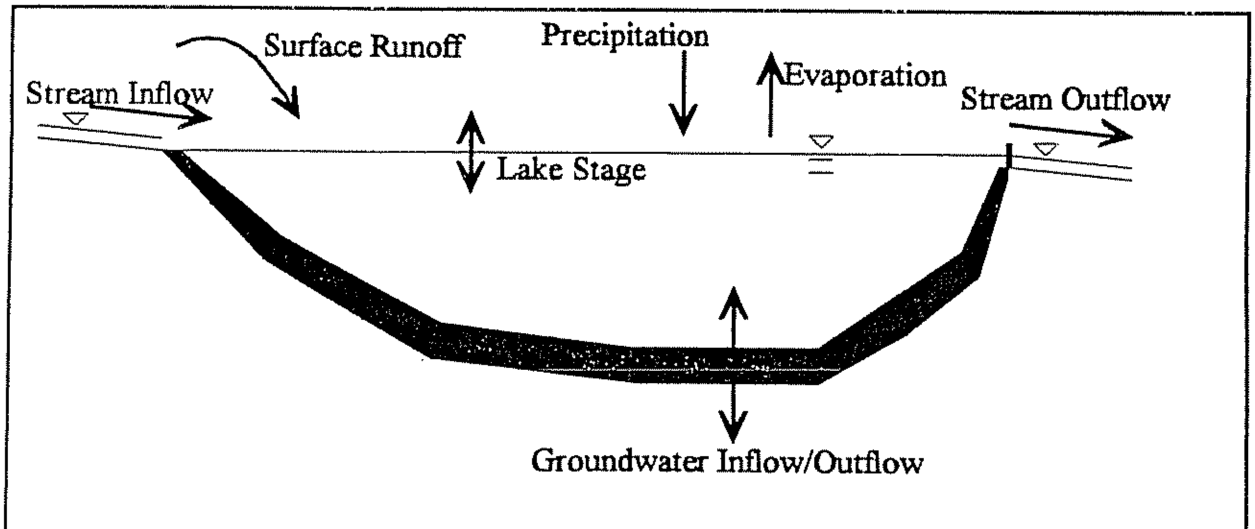

Figure 1. Cross-sectional view of a lake showing its volumetric budget components.

In equation (1) the dependent variable, h, is potentiometric head [L], a function of space and time. The independent variables are the spatially variable hydraulic conductivity (K_x, K_y and K_z) [L/T] and specific storage (S_s) [L^{-1}] fields. Together with initial conditions for head and various boundary conditions, MODFLOW uses a discretized, algebraic form of equation (1) to solve for the potentiometric head at every model cell at time steps within each simulated period.

Boundary conditions allowed by MODFLOW include the specified-head, specified-flux, and head-dependent flux types. Boundary conditions are specified in MODFLOW through its various packages, or modules, including: Recharge (RCH), Well (WEL), River (RIV), Drain (DRN), and Evapotranspiration (EVT). Another package was later added for streamflow routing (STR1, revised to STR2, Prudic, 1989).

Packages to Simulate Lake-Groundwater Interaction

At least two previously-documented packages have been written to simulate lakes with MODFLOW: the Reservoir package (RES1), and the original Lake package (LAK1). The Reservoir package (RES1, Fenske et al., 1996) works like the River (RIV) package, but allows for a specified, linearly-varying (in time) lake stage. The known stage is used to determine the number of cells that are covered by the lake at each time step, and to determine the amount of flow to and from the groundwater. The RES1 package was not designed to calculate the stage in response to environmental stresses, and it is not connected to the Streamflow Routing package.

The original Lake package (LAK1) developed by Xiangxue Cheng and Mary Anderson (Cheng, 1994, Cheng and Anderson, 1993) includes many of the functions in the newer LAK2 package. In providing boundary conditions for equation (1), LAK1 also behaves like the River package (RIV). Additionally, it calculates lake stage as a transient response to evaporation, precipitation, surface runoff, streamflow, and groundwater flux. The LAK1 package handles lake-stream interaction with a modified version of the original Streamflow Routing package (STR1). The package does not provide for steady-state solution of lake stage, and requires the use of Manning's equation to calculate flow from a lake to an adjoining stream, based on the stage in the lake.

The new Lake package (LAK2) described here includes all of the capabilities of the RES1 and LAK1 packages, and includes new features that were desired for modeling the proposed mine site in northern Wisconsin. First, computation of steady-state lake stage is possible, using a modified version of Newton's method. The steady-state lake stage represents the stage at which lake inflow (from precipitation on the lake, overland runoff, stream inflow, and groundwater flux) is balanced by lake outflow (to streams, groundwater, and the atmosphere via evaporation). Also, the relationship describing stream outflow has been made very general, to accommodate a wide variety of stage-outfall relationships. The LAK2 package is a completely new code, which improves the input file structure, output options, and memory requirements of the LAK1 package. It is easy to connect to MODFLOW, seamlessly connecting with the current Streamflow Routing package (STR2) for stream-lake interaction.

Other Lake-Groundwater Models

Lake packages for other groundwater flow models have previously been developed, as documented in Cheng and Anderson, 1993. Additionally, fully integrated surface-water and groundwater models have been and are being developed that vary in terms of capabilities and complexity (see Yan and Smith, 1994, for example).

LAKE PACKAGE DESIGN

The LAK2 Lake package provides two major functions: 1) it formulates boundary conditions for the system of equations MODFLOW uses to solve equation (1), and 2) it computes lake-wide budget and stage information. These two functions are related through the lakebed hydraulic conductance, which controls the degree of lake-groundwater interaction.

Groundwater Flow Boundary Condition

The head-dependent flux boundary formulation used by the Lake package is very similar to that used in the River (RIV) package, which specifies the flux through the lakebed or riverbed as a function of stage, head in the connected cells, and the lakebed or riverbed conductance. With the Lake package, the conductance at each cell is either specified in the input file or calculated by the program from the specified lakebed geometry and hydraulic conductivity.

As with the River package, flow from a lake to the groundwater is limited when the head in a cell falls below the lakebed bottom. Also, if the stage of a lake is below the top of the lakebed, the lake cell is dry and seepage into the groundwater is cut off for that cell.

Lake Volumetric Balance and Stage Computation

Once head values are obtained by MODFLOW, subroutines in the Lake package sum the inflows and outflows which can be used to update the lake stage. Simple volumetric equations are applied to update stage in steady-state and transient modes.

Steady-state stage. To solve for steady-state lake stage, the following volumetric-balance equation is applied (all flow terms have units of L^3/T):

$$Q_P + Q_{RO} + Q_{STRIN} = Q_{GW}(S) + Q_E(S) + Q_{STROUT}(S) \qquad (2)$$

In equation (2), which simply states that lake inflow equals lake outflow, the three terms on the right-hand-side are each a function of the lake stage, S. The total flux to the groundwater (Q_{GW}) is the sum of each lake cell's individual flux. The evaporative flux, Q_E is computed as the product of the user-specified evaporation rate and the "wetted" lake area, which includes only those cells with a lakebed top elevation below the lake stage. The total stream outflow, Q_{STROUT}, is the sum of any number of individual stream outflows, each computed (as a function of stage) with user-specified outflow relationships. The computed stream outflows are also assigned as the inflow terms for specified segments of the Streamflow Routing package.

The left-hand-side of equation (2) contains inflows that are independent of lake stage. The precipitation inflow, Q_P, is the product of the user-specified precipitation rate and the total lake area (when full). The runoff inflow, Q_{RO}, is specified by the user in the input file. The total stream inflow, Q_{STRIN}, is the sum of outflows from all stream reaches that are tributary to the lake, contained in the *ARTRIB* variable of the Streamflow Routing package.

When steady-state mode is specified for a lake, the steady-state stage is computed after each head solution approximation. In this manner, the stage remains in balance with successive approximations of groundwater head until the head solution converges. An efficient solution method, based on Newton's method is used to calculate steady-state stage in an iterative fashion. In this process, the derivative of outflow with respect to lake stage is calculated, which indicates the direction and approximate magnitude of stage change necessary to maintain a steady-state balance. Modifications to Newton's method allow for potential discontinuities in the outflow vs. stage relationship. Iteration stops when the lake stage is within a specified tolerance of the exact solution. The number of cells representing the lake may change as the stage is updated.

Transient stage. In transient mode, the stage is updated at every timestep, increasing when inflows exceed outflows and decreasing when outflows exceed inflows. For the first timestep, MODFLOW solves for potentiometric head, with the lake boundary conditions formulated using the specified initial lake stage. After the head solution is complete, lake inflows and outflows are summed to determine the volume change for the lake, ΔV during the timestep of length Δt:

$$\Delta V = \left(Q_P + Q_{RO} + Q_{STRIN} - Q_{GW} - Q_E - Q_{STROUT}\right)\Delta t \tag{3}$$

This volume change is added to the original volume to obtain the volume for the next timestep. The stage is then set by an iterative method (similar to that used for the steady-state stage solver) to a value that gives the appropriate volume. The number of cells representing the lake may change in this process.

Output options. The Lake package has many output options to aid in the interpretation of results. The status of each lake can be listed in a table in the main output file at the end of each simulation period. These tables include computed or specified stage, lake wetted area and water volume, all of the terms of equations (2) and (3), the total of all inflows and outflows, and the net flow (or steady-state volumetric balance error). Additionally, the stage and/or flow terms can be saved to a separate output file after each timestep, for easy loading into post-processing software or spreadsheets. Cell-by-cell flows between the lake and groundwater can be printed in the main output file or saved in MODFLOW's binary format for post-processing and linking to other programs (such as particle tracking and solute transport programs).

Code Testing

Several tests were performed on the Lake package to ensure that it correctly formulates the groundwater equations and properly calculates lake stage. For two test problems (Cheng and Anderson, 1993 and Cheng, 1994), the results of the LAK2 package were identical to those of LAK1. The steady-state and transient stage solvers were tested against hand calculations of volumetric balance for various test problems, and simulations were conducted to verify that the groundwater equations were being formulated in a manner identical to that used by the River (RIV) package.

EXAMPLE APPLICATION

A flow model using the Lake package was used to simulate lake-groundwater interaction near a proposed underground zinc and copper mine site located approximately 5 miles south of Crandon, Wisconsin. The 169 row, 137 column model extends over 57 square miles with cell widths ranging from 30 to 300 meters (100 to 1000 feet). Vertically, the model is discretized into seven layers that vary in thickness to follow the geologic stratigraphy. The upper four layers contain glacial till, glacial outwash, and lacustrine sediments. The lower three layers represent bedrock with differing degrees of weathering. The orebody to be mined is located in the bedrock layers.

The model was set up to predict what would happen once the mine goes into operation. As a result of mine dewatering, water would be removed from the bedrock system leading to a decrease in aquifer head and a decline in water levels in overlying lakes and streams. The model was used to predict the location and magnitude of groundwater drawdown, and the amount of lake stage decline at the nearest four lakes. These lakes are connected directly to the saturated groundwater, with no significant unsaturated zone beneath them.

The project's environmental impact report (Foth & Van Dyke, 1995) contains detailed discussions of the entire modeling process and the extensive field tests used to establish approximate ranges for model parameter values. This paper only touches on a small part of the ongoing modeling effort, concentrating on the simulated lakes.

Model Calibration

Before predictive simulations were performed, reasonable values for model/system parameters (such as aquifer hydraulic conductivity, lakebed conductivities, and other boundary conditions) were chosen. The selected parameter values resulted in a model that closely matched observed heads, lake levels, and streamflows. This process of calibration to past and current conditions was critical to producing meaningful predictions. Several calibration time frames were chosen to eliminate as much parameter uncertainty as practicable. For example, a seven-year transient simulation was conducted to determine how well the model could replicate water levels observed during a prolonged drought. With the most reasonable values assigned to model parameters, simulated lake levels closely followed the observed pattern of lake stage changes, as shown for one of the lakes in Figure 2.

Model Predictions

Once calibration quality was within the project's pre-defined goals, steady-state and transient predictive simulations were performed to estimate the hydrological effects of the proposed mine. Dewatering in the mine was simulated using MODFLOW's Drain (DRN) package.

In steady-state, the rate of mine inflow would be replaced by increased inflow from, or decreased outflow to, the various water bodies comprising the groundwater model's boundary conditions. A decrease in groundwater levels would affect the surface water components: wetlands, streams, and lakes. The predicted amounts of steady-state lake stage decline and stream outflow decline are listed in Table 1. The stage declines were markedly less at Little Sand Lake, Duck Lake, and Deep Hole Lake, than at Skunk Lake because lower-conductivity lacustrine deposits underlie the first three lakes, and beaver dams on the outgoing streams of these lakes play an important part in controlling lake stage.

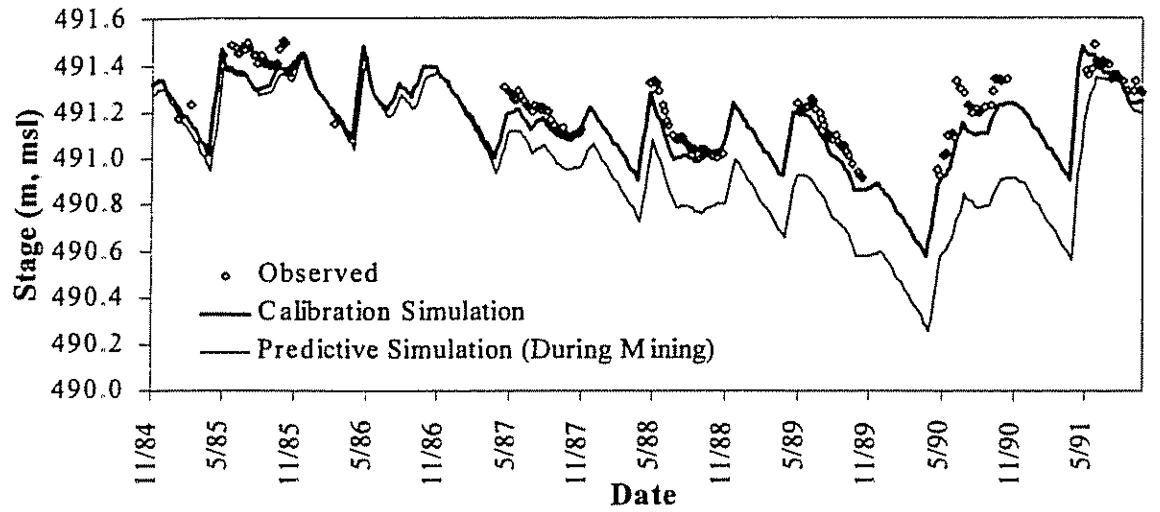

Figure 2. Observed and simulated lake stages for Duck Lake.

Table 1
Simulated Changes in the Steady-state Stages and Stream Outflows of Model Lakes.

Lake Name	Stage Before Mining (m, msl)	Stage During Mining (m, msl)	Stage Decline (m)	Stream Outflow Before Mining (m^3/d)	Stream Outflow During Mining (m^3/d)	Stream Outflow Reduction (m^3/d)
Deep Hole	489.430	489.417	0.012	493	354	139
Duck	491.319	491.277	0.043	61	12	48
Little Sand	485.132	485.120	0.012	1752	1005	746
Skunk	486.939	486.464	0.475	0	0	0

Transient simulations were used to predict the combined effect of mining operations and a natural drought. In Figure 2, the bottom line shows model-predicted lake stages during a drought that occurs well into the mining process (for this series, the date refers only to the precipitation/evaporation data used—the mine was not actually in operation during that period).

CONCLUSIONS

The LAK2 Lake package provides for the simulation of lakes with MODFLOW, effectively simulating lake-groundwater interaction. The package provides methods for computing the steady-state or transient lake stage, and integrates seamlessly with the Streamflow Routing package. LAK2 provides a broad range of features and capabilities that builds on those offered by the previously-documented packages RES1 and LAK1.

A demonstration of the usefulness of the Lake package is provided by the proposed mine site example. In steady-state and transient simulations, the Lake package predicts the lake level decline that would occur as a result of operating the underground mine.

ACKNOWLEDGMENTS

The LAK2 Lake package code development and the Crandon project modeling study were funded by the Crandon Mining Company and the Nicolet Minerals Company through their consultant, Foth & Van Dyke.

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Fenske, J.P., S.A. Leake, and D.E. Prudic, 1996. Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW), US Geological Survey Open-File Report 96-364.

Foth & Van Dyke, 1995. Environmental Impact Report for the Crandon Project. Submitted to the Wisconsin Department of Natural Resources in Madison and the US Corps of Engineers in St. Paul, MN.

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Yan, J., and K.R. Smith, 1994. Simulation of integrated surface water and ground water systems — model formulation, *Water Resources Bulletin*, Vol. 30, No. 5, pp. 879-890.

Section A.4.2

INPUT INSTRUCTIONS

Lake Package for MODFLOW, Version 2.2

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```
                          INPUT INSTRUCTIONS
                 Lake Package for MODFLOW, Version 2.2
                          GeoTrans, May 1996
                             Greg Council
--------------------------------------------------------------------
-----------

                          IDENTIFICATION LINE

/*LAK2.2
  format:  exactly as shown


                            SIMULATION DATA

NLAKES  ILKCBC  ILKOUT  IECHO  NSUBSTEPS
  format:  5I10

NAME  ISIMMODE  STSTAGE  ITERLAKE  CONVCRIT   (one line for each lak
e)
  format:  A10, I10, F10.0, I10, F10.0


                             PHYSICAL DATA
                        (one set for each lake)

NODES  NSTRIN  NSTROUT  STAGEMX  ICONDOP
  format:  3I10, F10.0, I10

ISEGIN                        (one line for each inflow stream)
  format:  I10

ISEGOUT  NRATEQ                                                    |
one set
  format:  2I10                                                    |
for each
                                                                   |
outflow
CUTOFF  CONST  ELEV  EXPNT  (one line for each rating equation)    |
stream
  format:  4F10.0           (sorted by CUTOFF, descending)         |

ILAY  IROW  ICOL  TOP  BOT  AREA  COND  (one line for each lake node
)
  format:  3I10, 4F10.0
```

STRESS PERIOD DATA
(one set for each stress period)

```
ITMP
  format:  I10

PRECIP  EVAP  RUNOFF  DRYRCH  IOUTOP  STAGE  (one line each lake if
ITMP >=0)
  format:  4F10.0, I10, F10.0
```


VARIABLE DESCRIPTIONS

```
NLAKES:     Number of lakes
ILKCBC:     >0 Cell-by-cell unit number, <=0 Do not save cell-by-cell
ILKOUT:     >0 Stage/Budget unit number, <=0 Do not write stage/budge
t records
IECHO:      <0 No input echoing, 0 Summary of input, >0 Full echoing
of input
NSUBSTEPS: Number of sub-time-steps for simulating lakes in transien
t mode

NAME:       Name (ID) of lake (10 characters)
ISIMMODE:   Simulation Mode:
            0 Fixed Stage, 1 Interpolated stage, 2 Steady-state, 3 Tr
ansient
STSTAGE:    Starting Stage (not required for ISIMMODE = 0)
ITERLAKE:   Max iterations for stage solver (ISIMMODE = 2 or 3)
CONVCRIT:   Stage solver termination criteria (change in stage in 1 i
teration,
            ISIMMODE = 2 or 3)

NODES:      Number of lake nodes
NSTRIN:     Number of inflow streams
NSTROUT:    Number of outflow streams
STAGEMX:    Maximum lake stage
ICONDOP:    <=0 Hydraulic conductivity input, >0 Conductance input

ISEGIN:     Inflow stream segment (from streamflow routing package)
ISEGOUT:    Outflow stream segment (from streamflow routing package)
NRATEQ:     Number of equations used to define stage-discharge relati
onship

CUTOFF:     Lower stage limit of rating equation
```

```
CONST:      Rating equation constant
ELEV:       Rating equation reference (outfall) elevation
EXPNT:      Rating equation exponent

               Outflow = CONST * (STAGE - ELEV)^ EXPNT  (Above CUTOFF
)

ILAY:       Lake node model layer (0 for top active layer)
IROW:       Lake node model row
ICOL:       Lake node model column
TOP:        Lakebed top elevation
BOT:        Lakebed bottom elevation
AREA:       Lake node area
COND:       Lakebed hydraulic conductivity or conductance (see ICONDO
P above)

ITMP:       <0 Use information from last stress period, >=0 read new
information
PRECIP:     Total area flow rate (L/T multiplied by total lake area,
            positive = inflow to lake, e.g. precipitation rate)
EVAP:       Wetted area flow rate (L/T multiplied by wetted lake area
,
            negative = outflow from lake, e.g. evaporation rate)
RUNOFF:     Fixed lake inflow (L^3/T, positive = inflow to lake, e.g.
 runoff)
DRYRCH:     Recharge rate applied to groundwater beneath dry lake cel
ls (L/T)
IOUTOP:     Output option, constructed as follows:
                 0  = no output
                 +1 = print cell-by-cell flows in main output file
                 +2 = print lake budget information in main output fi
le
                 +4 = write stage to stage/budget output file
                 +8 = write flows (& stage) to stage/budget output fi
le
            (e.g. 6 to print lake budget in main output file, write s
tage record
            to stage/budget output file)
STAGE:      If ISIMMODE = 0, lake stage for the stress period
            If ISIMMODE = 1, final lake stage for the stress period
            Ignored for ISIMMODE = 2 or 3
```

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Section A.4.3

USGS Report
Water Resources Applications Software
Summary of MODFLOW

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USGS REPORT

Water Resources Applications Software

Summary of MODFLOW

NAME

modflow - Modular three-dimensional finite-difference ground-water flow model

ABSTRACT

MODFLOW is a three-dimensional finite-difference ground-water flow model. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. This version includes all the major capabilities that were documented as of September 1996.

MODFLOW simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axes and the anisotropy ratio between horizontal coordinate directions is fixed in any one layer), and the storage coefficient may be heterogeneous. The model requires input of the ratio of vertical hydraulic conductivity to distance between vertically adjacent block centers. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for ground-water flow problems. An efficient contouring program is available (Harbaugh, 1990) to visualize heads and drawdowns output by the model.

METHOD

The ground-water flow equation is solved using the finite-difference approximation. The flow region is considered to be subdivided into blocks in which the medium properties are assumed to be uniform. The plan view rectangular discretization results from a grid of mutually perpendicular lines that may be variably spaced. The vertical direction zones of varying thickness are transformed into a set of parallel "layers". Several solvers are provided for solving the associated matrix problem; the user can choose the best solver for the particular problem. Mass balances are computed for each time step and as a cumulative volume from each source and type of discharge.

HISTORY

Version 2.6 1996/09/20 - Added Reservoir package (RES1) as documented in U.S. Geological Survey Open-File Report 96-364. Problem fixed for IBS package. Although subsidence is only meant to be active for layers in which IBQ>0, sometimes MODFLOW performed subsidence calculations when IBQ<0. Note that this was a problem only if negative IBQ values were specified. That is, the code has always worked correctly for IBQ=0 and IBQ>0.

Version 2.5 1995/06/23 - Added direct solution package (DE45).

Version 2.4 1995/06/15 - Added transient leakage package (TLK1).

Version 93/08/30 - Release with PCG2, BCF3, STR1, HFB1, ISB1, CHD1, and GFD1 additions.

Version 87/07/24 - Fortran 77 version published in U.S. Geological Survey Techniques of Water-Resources Investigations 6-A1.

Version 83/12/28 - Fortran 66 version published in U.S. Geological Survey Open-File Report 83-875.

DATA REQUIREMENTS

In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid.

OUTPUT OPTIONS

Primary output is head, which can be written to the listing file or into a separate file. Other output includes the complete listing of all input data, drawdown, and budget data. Budget data are printed as a summary in the listing file, and detailed budget data for all model cells can be written into a separate file.

SYSTEM REQUIREMENTS

MODFLOW-88 is written in Fortran 77 with the following extensions: use of variable names longer than 6 characters and the CARRIAGECONTROL option in OPEN statements. By default, the software is dimensioned for use with models having up to 90,000 cells. MODFLOW-88 uses preallocated files, which means that the file names are not assigned by Fortran OPEN statements. Instead, the compiler or operating system must provide a way to open the files. Example script files are provided to illustrate this procedure. Generally, the program is easily installed on most computer systems. The code has been used on UNIX-based computers and DOS-based 386 or greater computers having a math coprocessor and 4 mb of memory.

PACKAGES

This version of MODFLOW includes the following packages:

BAS1 -- Basic Package
BCF3 -- Version 3 of Block-Centered Flow Package

RIV1 -- River Package
DRN1 -- Drain Package
WEL1 -- Well Package
GHB1 -- General Head Boundary Package
RCH1 -- Recharge Package
EVT1 -- Evapotranspiration Package
SIP1 -- Strongly Implicit Procedure Package
SOR1 -- Slice Successive Over-Relaxation Package
UTL1 -- Utility Package
PCG2 -- Version 2 of Preconditioned Conjugate Gradient Package
STR1 -- Stream Package
IBS1 -- Interbed-Storage Package
CHD1 -- Time-Variant Specified-Head Package
GFD1 -- General Finite Difference Flow Package
HFB1 -- Horizontal Flow Barrier Package
TLK1 -- Transient Leakage Package
DE45 -- Direct solver
RES1 -- Reservoir Package

The user must specify values for the appropriate IUNIT array element to include packages not in the original model. The IUNIT array is interpreted according to the following table:

BCF3 -- IUNIT(1) -- same IUNIT as used for BCF1 because BCF3 replaces BCF1
TLK1 -- IUNIT(6)
DE45 -- IUNIT(10)
PCG2 -- IUNIT(13)
GFD1 -- IUNIT(14)
HFB1 -- IUNIT(16)
RES1 -- IUNIT(17)
STR1 -- IUNIT(18)
IBS1 -- IUNIT(19)
CHD1 -- IUNIT(20)

The input unit for the Basic Package is unit 5, which is defined by the assignment of variable INBAS in the MAIN program.

DEPENDENCIES AMONG PACKAGES

As documented in Open-File Report (OFR) 94-59, the Transient Leakage (TLK) Package does not simulate flow through a confining unit at any horizontal grid location at which a cell on either side of the confining unit is dry. When this situation occurs as a result of initial conditions, the user can determine if this is appropriate before making a simulation. However, a cell can go dry at any time during a simulation when using the water-table or convertible layer options in the Block-Centered Flow (BCF) Package. When a cell goes dry on either side of a confining unit, the transient leakage through the confining unit immediately becomes zero at that horizontal location. Users should check simulations to see if cells on either side of a confining unit are going dry at any time during a simulation and determine if it is acceptable for the transient leakage to switch to zero. Further complications can result when using the wetting capabilities of version 2 of the BCF Package. If dry cells convert to wet so that cells on both sides of a confining unit are wet, then transient leakage calculations will be started; however, the equations will not be properly formulated to simulate the previous conditions, so the transient flow will not be correct. Thus, the wetting capability should not be used for any model layers that connect to a confining unit that is being simulated with the

TLK Package.

The Time-Variant Specified-Head (CHD) Package can potentially cause the TLK Package to operate incorrectly if the CHD Package is being used to specify constant heads at cells on either side of a confining unit. The TLK Package relies on initial head as defined by the Basic Package to setup initial parameters. If the data for the CHD Package define initial heads (i.e., head for the first time step of the simulation) on either side of a confining unit to be different than defined by the Basic Package, the transient leakage calculations will be incorrect. To avoid this conflict, do not use the CHD Package to define constant head cells on either side of a confining unit, or be sure that the initial head in the Basic Package exactly matches the initial head defined by the CHD Package.

DOCUMENTATION

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Version 2 of Preconditioned Conjugate Gradient Package is documented in:

Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.

The Stream Package is documented in:

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

The Interbed-Storage and Time-Variant Specified-Head Packages are documented in:

Leake, S.A., and Prudic, D.E., 1988, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 88-482, 80 p.

The General Finite Difference Flow Package is documented in:

Harbaugh, A.W., 1992, A generalized finite-difference formulation for the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-494, 60 p.

The Version 2 of the Block-Centered Flow Package is documented in:

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1992, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-536, 99 p.

The BCF3 Package is documented in three pieces. It builds on two previous versions of the Block-Centered Flow (BCF) Package. Documentation for the BCF1 Package describes the fundamental function of all BCF Packages. This documentation is contained in the basic model documentation (McDonald and Harbaugh, 1988). BCF2 documentation describes the addition of the capability to convert dry cells to wet:

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1992, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-536, 99 p.

BCF3 documentation describes the addition of alternate interblock transmissivities. The BCF3 code includes the capabilities of BCF1 and BCF2:

Goode, D.J., and Appel, C.E., 1992, Finite-difference interblock transmissivity for unconfined aquifers and for aquifers having smoothly varying transmissivity: U.S. Geological Survey Water-Resources Investigations Report 92-4124, 79 p.

The HFB1 Package is documented in:

Hsieh, P.A., and Freckleton, J.R., 1993, Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 92-477, 32 p.

The Transient-Leakage Package (TLK1) is documented in:

Leake, S.A., Leahy, P.P., and Navoy, A.S., 1994, Documentation of a computer program to simulate transient leakage from confining units using the modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-59, 70 p.

The DE45 Package is documented in:

Harbaugh, A.W., 1995, Direct solution package based on alternating diagonal ordering for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 95-288, 46 p.

The RES1 Package is documented in:

Fenske, J.P., Leake, S.A., and Prudic, D.E., 1996, Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 96-364, 51 p.

RELATED DOCUMENTATION

Harbaugh, A.W., 1990, A simple contouring program for gridded data: U.S. Geological Survey Open-File Report 90-144, 37 p.

REFERENCES

MODFLOW is widely used in the USGS and throughout the world.

Belitz, K., and Phillips, S.P., 1993, Numerical simulation of ground-water flow in the central part of the western San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 2396, 69 p.

Prince, K.R., Franke, O.L., and Reilly, T.E., 1988, Quantitative assessment of the shallow ground-water flow system associated with Connetquot Brook, Long Island, New York: U.S. Geological Survey Water-Supply Paper 2309, 28 p.

TRAINING

Modeling of Ground-Water Flow Using Finite-Difference Methods (GW2096TC), offered annually at the USGS National Training Center.

Advanced Finite-Difference Modeling of Ground-Water Flow (GW3099TC), offered annually at the USGS National Training Center.

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Official versions of U.S. Geological Survey water-resources analysis software are available for electronic retrieval via the World Wide Web (WWW) at:

http://water.usgs.gov/software/

and via anonymous File Transfer Protocol (FTP) from:

water.usgs.gov (path: /pub/software).

The WWW page and anonymous FTP directory from which the MODFLOW software can be retrieved are, respectively:

http://water.usgs.gov/software/modflow.html
--and--
/pub/software/ground_water/modflow

If you would like to obtain the price of and (or) order paper copies of USGS reports, contact the USGS Branch of Information Services at:

U.S. Geological Survey
Branch of Information Services
Denver Federal Center, Box 25286
Denver CO 80225-0286

To inquire about Open-File Reports or Water-Resources Investigations Reports:

Tel: 303-202-4210; Fax 303-202-4695

To inquire about other USGS reports:

Tel: 303-202-4700; Fax 303-202-4693

A.5 REFERENCES

Cheng, X. and M.P. Anderson

1993 Numerical simulation of ground-water interaction with lakes allowing for fluctuating lake levels. Ground Water. v. 31:6, pp. 929-933.

Fenske, J.P., S.A. Leake, and D.E. Prudic

1996 Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW), US Geological Survey Open-File Report 96-364.

Harbaugh, A.W., and McDonald, M.G.

1996 User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96–485, 56 p.

McDonald, M.G. and A.W. Harbaugh

1988 A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Book 6, Ch. A1 of Techniques of Water-Resources Investigations of the U.S. Geological Survey.

Prudic, D.E.

1989 Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model, US Geological Survey Open-File Report 88-729.

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1994 Simulation of integrated surface water and ground water systems — model formulation, Water Resources Bulletin, Vol. 30, No. 5, pp. 879-890.

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APPENDIX B GROUNDWATER MODEL USER'S MANUAL

APPENDIX B
GROUNDWATER MODEL USER'S MANUAL

B.1 DESCRIPTION OF NUMERICAL MODEL

The design, construction, and calibration of the groundwater model is documented in Section 6 and Appendix A of this report. This section briefly discusses the manner in which key model input data was manipulated and entered into model input data files for model execution. The reader should be familiar with standard MODFLOW input file format or refer to the references in Appendix A for background on model input and output files. MODFLOW96, in particular, has a concise summary of model input file construction.

Much of the data for the SSA groundwater flow model was maintained in a Geographic Information System (GIS) Database to automate the construction of the large arrays required for the MODFLOW input files. These input files were then modified using a visual MODFLOW preprocessor (Groundwater Vistas, 1999) during model calibration and prediction simulations.

B.1.1 Layer Elevation Data

Layer elevation data are contained in the *.BCF MODFLOW input file. These data were derived from the stratigraphic model discussed in Sections 3 and 6, and are shown in the topographic layer contours in Appendix G. Modifications to these arrays can be made by creating an array using contouring or interpolation software with 186 rows and 103 columns that covers the entire model area (minus ¼ mile on each model side to account for the block centered grid block formulation in MODFLOW). The array data must then be formatted in the desired MODFLOW format and edited into the appropriate location in the *.BCF file.

B.1.2 Hydraulic Conductivity Data

Hydraulic conductivity data are contained in the *.BCF MODFLOW input file. These data are shown in the hydraulic conductivity contours in Section 6, which were initially derived from both the Imperial County Groundwater Model (Montgomery Watson, 1995) and the USBR Model (Bureau of Reclamation,

1988) and later modified during model calibration as discussed in Section 6. Modifications to these arrays can be made as summarized in Section B.1.1.

B.1.3 Boundary Condition Data

Data describing boundary conditions are input in several MODFLOW files depending on the type of boundary conditions. Inactive cells that create model no-flow boundaries depicted by the inactive area in the figures in Section 6 are entered in the IBOUND array in the MODFLOW *.BAS file. Initial model heads were estimated using the 1960/65 composite water level contour map in Figure 3-1, and are contained in the MODFLOW *.BAS file. Time varying boundary constant heads were derived by interpolation from Figures 3-1 and 3-2 and the figures in Appendix F and are contained in the MODFLOW *.CHD file.

Drain input data for the New and Alamo Rivers was derived from river topographic data and are contained in the *.DRN file. Stream input data used for the AAC, CB, and East Highline canals were derived from canal topographic data and are contained in the *.RIV file. Lake input data for the Salton Sea were derived from bathymetry data and are contained in the *.LAK file (see also Section A.4). General head boundary data were estimated from known fluxes between the Cargo Muchacho mountains and Pilot Knob, and the Cargo Muchacho and Chocolate mountains; the general head boundary data are contained in the *.GHB file.

B.1.4 Other Model Data

Groundwater extraction data for the Mesquite and American Girl Mines were derived from the Imperial County Groundwater Model (Montgomery Watson, 1995), and are contained in the *.WEL file. Evapotranspiration data were derived from previous analyses of the wetlands (see Sections 4 and 5) and are contained in the *.EVT file. Recharge due to precipitation was estimated at 0.02 inches per year, and the data are contained in the *.RCH file. Fault data were derived from geologic maps and by model calibration, and are contained in the *.HFB file.

Other model data which relates to the model water balance such as canal leakage rates were not hard-wired as recharge rates in the model and they are entered using the River package (*.RIV). In order to modify canal recharge rates, the river stage, bed, or conductance data in the *.RIV files must be modified.

B.1.5 Key Model Assumptions

This section presents a brief discussion of the assumptions used in the mathematical model, including features of the model, assumptions about lateral anisotropy, boundary conditions, mesh size, time steps, which items change during time steps and which are constant, and other assumptions and generalizations.

The New and Alamo Rivers were treated as drain features using the MODFLOW model, which assumes that groundwater inflow into these rivers can be simulated using the methodology employed in MODFLOW for drains. All canals were treated as river features using the MODFLOW model, which assumes that groundwater inflow or outflow into these canals can be simulated using the methodology employed in MODFLOW for rivers. The aquifer was modeled to be laterally isotropic given that neither the data nor the geologic environment suggests the aquifer is laterally anisotropic. Boundary conditions are discussed in detail within the report, with the La Mesa Drain treated as a time-varying head boundary, the Pilot Knob area as a general head boundary, and the IID area as a constant head boundary, which assumes that groundwater inflow or outflow at these locations can be simulated using the methodology employed in MODFLOW for these boundary types.

The mesh size was set to one-half mile in order to resolve the local seepage and canal features. Time steps are set to one-year time periods, except immediately following stress changes in 1979 and 2006 when time steps are ramped up from monthly to yearly values. During transient runs, the only model input parameters which change are the time-varying boundary heads and boundary flux from Coachella Valley into the Salton Sea. Canal seepage factors change twice, once in 1979 at the transition from the steady-state calibration to the transient calibration, and once in 2006 at the AAC and CB lining, but they do not vary within a transient run segment. All other model input parameters are not time variable.

B.2 GROUNDWATER FLOW MODEL

This section provides brief instructions for running the groundwater flow model using MODFLOW96. Additional notes are included to utilize Groundwater Vistas for pre- and post-processing. The majority of MODFLOW files provided with this report were created using Groundwater Vistas. Note the model must be run using MODFLOW96 with the Lake Package to reproduce the model results given in this report.

B.2.1 Provided CD Directory Structure

The files included with this report are subdivided into several directories based on the simulation (steady-state or transient), and the model software (Groundwater Vistas or MODFLOW96). Files created in Groundwater Vistas were transferred from that directory to the MODFLOW96 (MF96) directory to run the simulations.

C:\SSA_CD\Steady-State\MF96
C:\SSA_CD\Transient\MF96

B.2.2 Model Input Files

The following Groundwater Vistas model input files were distributed with this report:

RUN1N.GWV	Steady-state simulation (represents 1979 conditions)
RUN1NT.GWV	Transient simulation (represents 1979 to 2006 conditions)
RUN1PT.GWV	Transient simulation (represents 2006 to 2026 conditions with canal linings)
RUN1QT.GWV	Transient simulation (represents 2006 to 2026 conditions without canal linings)
RUNTOSS.GWV	Transient simulation (represents long term SS conditions with canal linings)

The following MODFLOW96 model input files for each simulation was distributed with this report:

RUN*.BAS	basic model input data
RUN*.BCF	model construction and hydraulic data

RUN*.CHD	time varying constant head cells (transient simulations only)
RUN*.DRN	drain elevation and conductance data
RUN*.EVT	evapotranspiration data (transient simulations only)
RUN*.GHB	general head boundary data
RUN*.HFB	horizontal flow barrier data
RUN*.LAK	lake data
RUN*.OC	model output control
RUN*.PCG	PCG solver options
RUN*.RCH	recharge data
RUN*.RIV	river elevation and conductance data
RUN*.WEL	well location and pumping schedules

The data contained in each is briefly documented in Section B.1. All files are needed to run the model. The CHD file created by Groundwater Vistas for simulation RUN1PT was not used in running MODFLOW96 and should not be used in place of the CHD file provided.

B.2.3 Model Batch Files

Within the MF96 directory a batch file is included that automatically runs MODFLOW96. The batch file calls all relevant MODFLOW96 input files and creates all relevant MODFLOW96 output files. Additionally, the batch file will change the MODFLOW96 format head save (*.HED) and cell-by-cell flow (*.CBC) output files to Groundwater Vistas format (*.HDS and *.CBB, respectively). Although this step is not necessary for use in MODFLOW96 it is included for Groundwater Vistas users.

The following model batch files for each simulation were distributed with this report:

RUNLAK1N.BAT	model simulation RUN1N batch file
RUNLAK1NT.BAT	model simulation RUN1NT batch file
RUNLAK1PT.BAT	model simulation RUN1PT batch file
RUNLAK1QT.BAT	model simulation RUN1QT batch file
RUNLAKSS.BAT	model simulation RUNTOSS batch file

B.2.4 Model Output Files

The following model output files were distributed with this report:

RUN*.OUT	text model output summary
RUN*.HED	unformatted model head save data (MODFLOW96)
RUN*.HDS	binary model head save data (GW VISTAS)
RUN*.CBC	unformatted model water budget data (MODFLOW96)
RUN*.CBB	binary water budget data (GW VISTAS)
RUN*.STG	lake package stage file (transient simulations only)

Only the text *.OUT file can be viewed directly, and a post-processor is required to view the binary file data. However, the *.OUT file also contains limited model head and drawdown output arrays, as well as an echo of the model input data; model execution and error messages; mass balance summaries; and lake stage data for the steady-state simulation. Head save and cell-by-cell data was output for the beginning and ending time step of each stress period. Additional data was output based on period length, which varied by simulation. Review of the Output Control file (*.OC) will reveal which additional time steps were output. Note that the transient cell-by-cell output files are zipped up in file "CBB_CBC.zip" due to the large size of these files (>70MB each). Lake stage data for each time step are located in the *.STG files. Drawdown files (*.DDN) were not included, but can be created by modifying the .OC file and re-running the desired simulation.

B.2.5 Model Execution

The model must be executed with the MODFLOW96 version with the Lake Package (MODFL96.EXE) that was distributed with this report using the batch job file RUN*.BAT (Section B.2.3). To execute the model, copy all input files, the batch file RUN*.BAT, and the executable MODFL96.EXE into a single directory. Then, type "RUN*.BAT" at the DOS prompt in the same directory. The model execution time will vary based on the simulation run and individual computer processing speed. The output files listed above will be created. Note that output files will automatically be overwritten when simulations are re-run if they are located in the same directory, so a backup copy should be maintained elsewhere.

B.2.6 Model Pre- and Post-Processing Using Groundwater Vistas

Changes to file paths are required to run the simulations in Groundwater Vistas properly on individual computers. Specifically, the paths to model executables (including the working directory), paths to Groundwater Vistas base maps, and the starting heads files need to be modified based on the user's directory structure.

It is recommended that MODFLOW96 files be kept in a directory separate from the directory (working directory) in which Groundwater Vistas files are created (similar to the structure on the CD provided) to prevent overwriting files modified specifically for MODFLOW96. After new files are created, transfer the desired files to the MODFLOW96 directory (MF96 on CD) to run the simulation.

When accessing output files for display and analysis in Groundwater Vistas it is necessary to "browse" for the appropriate files as Vistas defaults to its "working directory", which should be different than the MODFLOW96 directory in which the simulations were run.

The Basic Package (*.BAS) created by Groundwater Vistas must be modified for MODFLOW96 to call the Lake Package (*.LAK). The unit number for the Lake Package (39, for the simulations provided) must be added in IUNIT location 15.

As stated in Section B.2.2, the CHD file created by Groundwater Vistas for simulation RUN1PT is not used, and should be modified outside of Groundwater Vistas.

B.3 REFERENCES

Bureau of Reclamation
1988 *Colorado River Water Underground Storage and Recovery Study, Imperial County, California*.

Groundwater Vistas
1999 Environmental Simulations, Inc., Oak Hill, VA 20171, Version 2.1, Internet address www.groundwatermodels.com

Montgomery Watson
1995 *Imperial County Groundwater Study, Final Report*.

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APPENDIX C CONCEPTUAL MODEL WATER BALANCE CALCULATIONS

APPENDIX C
CONCEPTUAL MODEL WATER BALANCE CALCULATIONS

Many conceptual model water balance calculations are given in the AAC and CB EIR reports, and all calculations from the EIR reports are not repeated here in the interest of brevity. Additional documentation and more detailed cross-references to the AAC and CB EIR reports is given in this report in Appendix C on key items such as the canal seepage rates. The reader can find additional documentation on other topics of interest in the AAC and CB EIR reports.

AAC

Disconnected Canal Seepage Rates

Total Seepage in connected reach (Pilot Knob to Drop 1, Table 4-1)	59,187 af/yr
Length of reach	73,392 feet
Canal width+height	205 feet

Seepage rate = (59,187 af/yr) (43,560 sq ft/acre)/(73,392 ft) (205ft) (365.25 day/yr) = 0.47 ft/day

Connected Canal Seepage Rates

Total Seepage in connected reach (Drop 2 to Drop 3, , Table 4-1)	7,415 af/yr
Length of reach	28,512 feet
Canal width+height	185 feet

Seepage rate = (7,415 af/yr) (43,560 sq ft/acre)/(28,512 ft) (185 ft) (365.25 day/yr) = 0.17 ft/day

Individual seepage rates for all other reaches are given in 8 pages of text, tables and figures in the AAC EIR Geohydrology Appendix starting on page 28.

CB

Canal Seepage Rates for Sandy Reach

Total Seepage in sandy reach (hydrologic unit C, Table 5-1)	11,410 af/yr
Length of reach	38,650 feet
Canal width+height	70 feet

Seepage rate = (11,410 af/yr) (43,560 sq ft/acre)/(38,650 ft) (70 ft) (365.25 day/yr) = 0.5 ft/day

Canal Seepage Rates for Clay/Lake Sediments Reach

Total Seepage in connected reach (hydrologic unit B, Table 5-1)	2,640 af/yr
Length of reach	31,258 feet
Canal width+height	70 feet

Seepage rate = (2,640 af/yr) (43,560 sq ft/acre)/(31,258 ft) (70 ft) (365.25 day/yr) = 0.14 ft/day

Individual seepage rates for all other reaches are given in 23 pages of text, tables, and figures in the CB EIR Geohydrology Appendix starting on page 7.

APPENDIX D PEER REVIEW FINAL REPORT

June 12, 1999

Mr. Thomas F. Field, R.G., C.H.G.
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348 W. Hospitality Lane, Suite 300
San Bernardino, CA 92408-3216

Subject: Peer Review Panel Report On SSA Study on Seepage And Subsurface Inflows To Salton Sea And Adjacent Wetlands

Dear Tom:

We have reviewed the May 26, 1999 report entitled: "75% submittal - A Study on Seepage and Subsurface Inflows to Salton Sea and Adjacent Wetlands" prepared for the Salton Sea Authority. As part of the peer review process, we reviewed relevant documents and reports and attended two technical workshops (28-Apr-99 and 3-Jun-99) with representatives from Tetra Tech, HSI Geotrans, Coachella Valley Water District, and the Imperial Irrigation District. In addition, the peer review panel met separately on 7-Jun-99. The comments and recommendations contained herein represent the joint effort of the peer review panel members.

In summary, the model is conceptually sound, provides reasonable values, and can be used for the intended purpose of the seepage and underflow estimates. Predictions made using the model are also reasonable within the limits of the data provided. Our comments focus on the following three areas:

- Conceptual Models - Ground Water And Water Balance
- Suitability Of The Ground Water Model To Quantify The Reduction In Seepage And Subsurface Inflows To The Salton Sea
- Recommendations For Improvements And Future Work

Conceptual Models - Ground Water And Water Balance

In general, the ground water model is conceptually sound. That is, the model's three layers, overall area of interest, boundary conditions, and related MODFLOW packages are appropriate for the geologic and hydrologic conditions encountered in the area and the intended purpose of the model. The model is calibrated against the 1979 observed water balance as well as the ground water level history in a number of wells. Based on the information available, the model appears to reasonably replicate the water supply and disposal items in the balance as well as the ground water level history in most model areas.

The conceptual model generally describes flows associated with surface features based on existing data, but does not include an error budget. Thus the numbers presented probably appear more certain than they really are. Ground water flow calculations are less well described. Inadequate descriptions are noted relating to the ground water flow calculations. However, the order of magnitude of the numbers appears reasonable.

The vegetation water balance, although simple in concept, assumes a constant evapotranspiration rate. The actual rate used in the calculations is not indicated in Section 8 of the report. However, earlier in the report, reference is made to 4 and 5 feet per year as given by the US Bureau of Reclamation. Since this is 20% uncertainty, and the total is a large fraction of the water balance, uncertainty in this number will directly affect the calculations. In reality, this number may be expected to increase in dry years and decrease in wet years. It may also depend on the maturity of the vegetation, and such events as rangeland fires. The calculations indicate four or five significant digits; this should be rounded to reflect the actual uncertainty in this number.

The following findings are consistent with the models. The geology of the northeast shore of the Salton Sea precludes any significant subsurface flow to the Salton Sea. The low-permeability lake clays preclude subsurface flow and restrict infiltration of surface water. Other than the active and formerly active channels of Salt Creek, little subsurface flow could be reasonably expected. As a result, the major portion of available water supply is consumed by native vegetation with little or no subsurface flow to the Salton Sea.

The conceptual model for ground water discharge summarizes total flows calculated in sections 3, 4, and 5 of the report. Ground water flows are constrained by two major features of the ground water basin between the All-American Canal and the Salton Sea. First, the ground water basin is essentially full from a few miles north of the AAC to the Salton Sea, and second, the tile drain network prevents heads from rising above the levels of the tile drain except during floods. Thus, the effects of head changes caused by lining the canals is restricted to a small part of the area modeled.

The conclusion that the change in discharge attributable to the mound beneath the canal cannot be calculated is not entirely justified. The hydraulic gradient is fixed by such features as the elevations of the base of the East Highline canal, the tile drain network and the Salton Sea. Therefore, all northbound ground water originating in the mound formed beneath the AAC is intercepted by the drainage features before it reaches the Salton Sea. The flow volume to the drainage features is proportional to the height of the mound. The volume of water is limited by the hydraulic conductivity, which changes very little by collapsing the mound. Collapsing the mound will approximately halve the gradient, and, assuming the water levels revert to 1939 levels beneath the mound, the ground water flow rate contribution to the drains will be approximately half. A hand calculation of this would provide a way to check the reasonableness of the computer model.

A related problem with the conceptual model of the ground water balance is that it does not attempt to identify the current contribution of the seepage mound to flow rates in the drains. Although this is discussed to some extent elsewhere in the text, it is also relevant here.

Suitability Of The Ground Water Model To Quantify The Reduction In Seepage And Subsurface Inflows To The Salton Sea

The ground water model's ability to predict the effects of management decisions is limited by several factors. Models have inherent limitations based on translation of the real system to mathematical terms, and they have other limitations based on the quality of the input. The appendix should include a short discussion of the assumptions used in the mathematical model, including features of the model, assumptions about lateral anisotropy, boundary conditions, mesh size, time steps, which items change during time steps and which are constant, and other assumptions and generalizations used. Although some of these items are described, their limitations are not. The overall effect is to make the model seem more robust than it may really be.

This model did not involve generating any new data, instead, existing sources were relied on for all data used. Many of the water budget items have considerable uncertainty, and many of the largest items may have uncertainties of 20 percent or more. Items notorious for wide ranges in uncertainty include evapotranspiration, underflow, and rising water. The quality of data and the range of uncertainty for each item should be tabulated. The results of mathematical computer models may appear more certain than they really are. This problem is most apparent in the excessive significant digits carried by the model.

The magnitude of the seepage into the Salton Sea, around 7,000 acre-feet per year, is well within the uncertainty of many of the large water balance items. Therefore, any item with an uncertainty of this magnitude could affect the range of the seepage estimate. The results of sensitivity analyses for larger flow items should be included.

One effect tabulated but not discussed is the effect of mound collapse on leakage out of the East Highline canal.

The model is designed to model hydraulic heads in the horizontal plane. The observation wells that are constructed of open, 1-inch galvanized pipe may be influenced by vertical components of flow. This will introduce error into the model calibration when heads are considered. Vertical errors of several feet are possible, particularly near the canals. Other wells may be screened below the modeled aquifers, or across the aquitard (layer 2). Problems with the calibration wells may mean hydrographs at odds with the transient or steady-state calibrations, and several problems with wells are apparent. Where the causes of discrepancies is known or suspected, they should be noted either in the text or figures.

Evapotranspiration (EVT), as noted above, is a significant portion of the balance, yet has been calculated using a single value of a number that has a minimum 20% uncertainty. In addition, actual EVT may vary in years that are cooler or warmer or wetter or drier than normal. Because both canal seepage and EVT are calculated, but their sum is constrained, any error in one makes an equal and opposite error in the other. In any flow-based model such as this one, the largest and most sensitive flows should receive the most effort to reduce uncertainty.

However, it should be recognized that each item of inflow and outflow is subject to a range of potential error. These errors can result in variations in the predictions of the water that may be lost to the Salton Sea and adjacent wetlands from the lining of the AAC and CB. For example, the combined estimated boundary underflow and drain flow of the La Mesa Drain is several times the predicted amount of water lost to the Salton Sea due to canal lining.

Recommendations For Improvements And Future Work

Some areas of the ground water model seem better calibrated than others. These areas need to be discussed as to how the difference between model generated ground water levels and historical levels impact the estimates of canal seepage and inflow to the Salton Sea. In general, more effort may be needed in model calibration if these "residuals" show an impact.

The ground water model reasonably duplicates steady flow conditions for the flows used. However, some of the flow items are less certain than they appear. The transient simulation extends the steady state assumptions to cover the recent past to the present. The projected changes due to the project are based on the transient calibration.

Although the mathematical model seems to be providing reasonable results, more sensitivity runs and error budget analysis may be warranted in the future, since the magnitude of the effects being sought are small in relation to the size of the input uncertainties.

It would be helpful to develop a table similar to Table 6-1 which would present an estimated error budget for each of the named features in the table.

Because of the uncertainty of the accuracy of the water budget item, all values should be rounded to the nearest 1,000 acre feet. This is particularly true of the model predicted values.

Investigation on the suitability of the 1 in. galvanized pipes for use in model calibration should be justified with reference to the point and average head concept as discussed above.

Sincerely,

REGISTERED GEOLOGIST
ALICE MARIE CAMPBELL
No. 1157
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President
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Tetra Techs' Response to Peer Review Panel Report
SSA Seepage Study

The following items summarize key points in the Peer Review Panel Report for the SSA Seepage Study and Tetra Techs' methodology for rectifying these points:

1) Page 2, 2nd Paragraph, Sentences 3 and 4.
Comment: *Ground water flow calculations are less well described. Inadequate descriptions are noted relating to the ground water flow calculations.*

Response: Most of these calculations were given in the AAC and CB EIR reports. Additional documentation will be added to this report in Appendix C on key items such as the canal seepage rates. More detailed cross-references to the AAC and CB EIR reports will also be added to Appendix C.

2) Page 2, 3rd Paragraph, Sentence 7.
Comment: *The calculations indicate four or five significant digits; this should be rounded to reflect the actual model uncertainty in this number.*

Response: The data from these tables are taken directly from the AAC and CB EIR reports and Tetra Tech is simply repeating the actual values as cited in the reference. The actual uncertainty in the EVT numbers will be qualified as discussed in the response to item number 6 below.

3) Page 3, 1st Paragraph, Last Sentence.
Comment: *Thus, the effects of head changes caused by lining the canal is restricted to a small /part of the area modeled.*

Response: The effects of head changes caused by lining the canal may be restricted to a small part of the area modeled, but the effects of flux changes caused by lining the canal, which is the primary focus of this study, is not restricted to a small part of the area modeled. Note that after canal lining, changes in flux are observed within the IID area drains as well as in the East Highline Canal.

4) Page 3, 2nd Paragraph, Sentence 6 and 7.
Comment: *Collapsing the mound will approximately halve the gradient and, assuming the water levels revert to 1939 levels beneath the mound, the groundwater flow rate contribution to the drains will be approximately half. A hand calculation of this would provide a way to check the reasonableness of the computer model.*

Response: The computer model predicts that the groundwater flow rate to the tile drains in 2026 if the AAC and CB canals remain unlined is about 21,770 afy. The model predicts that the steady-state flow rate after lining the canals is about 9,230 afy. Thus, the post-lining groundwater flow rate contribution to the drains is predicted to be just over 40 percent of the pre-lining value. This value is in good agreement with the expectation that the flow rate would be approximately half of the pre-lining value, considering that the one-half figure incorporates several assumptions and/or approximations. Since the model agrees with the expectation, a hand calculation is not necessary. The text will be modified to remove the conclusion indicating that the change in discharge attributable to the mound cannot be calculated.

5) Page 3, Last Paragraph, Sentence 3.
Comment: *The appendix should include a short discussion of the assumptions used in the mathematical model, including features of the model, assumptions about lateral anisotropy, boundary conditions, mesh size, time steps, which items change during time steps and which are constant, and other assumptions and generalizations.*

Response: Text will be added to Appendix A expanding on model assumptions and limitations. Note that Section 6 of the 75% submittal discussed the assumptions regarding boundary conditions.

6) Page 4, 2nd Paragraph, Sentence 4.
Comment: *The quality of data and the range of uncertainty for each item should be tabulated.*

Response: The water budget tables will be modified to indicate the range of uncertainty for each item. Note, however, that it may not be possible to define the exact level of uncertainty in all water budget items due to the varied sources referenced for the water budget. The scope of this study called for building upon the work of previous investigations to construct the SSA seepage model, and it was not possible within this study to independently verify all water budget components. Tetra Tech did, however, review all previous investigations and found that the data appeared reasonable and were from reliable sources such as the USGS.

In order to address the Peer Review Panel's concerns, Tetra Tech has modified the water budget table by adding a category with the relative level of uncertainty in each item. The level of uncertainty for each item will be established by a qualitative assessment of the type of data, the manner in which the data were estimated, and the degree to which independent investigations agree or disagree on each item.

7) Page 4, 4th Paragraph.
Comment: *One effect tabulated but not discussed is the effect of mound collapse on leakage out of the East Highline Canal.*

Response: Text will be added regarding the change in leakage out of the East Highline Canal.

8) Page 4, 5th Paragraph, Last Sentence.
Comment: *Where the causes of discrepancies is known or suspected, they should be noted either in the text or figures.*

Response: Text will be added regarding the causes of discrepancies.

9) Page 5, 1st Paragraph, Last Sentence.
Comment: *In any flow-based model such as this one, the largest and most sensitive flows should receive the most effort to reduce uncertainty.*

Response: Tetra Tech agrees in general with this statement, noting that for this very reason significant effort was devoted to matching the metered canal seepage looses. Uncertainty cannot always be reduced, however. For example, flows in Mexicali represent a large component of the water budget, but there was only limited data available which was of unknown quality.

Tetra Tech's scope of work did not call for conducting new field investigations to reduce uncertainty, and we were required to make use of the data currently available. Some key elements of the water budget, such as the amount of water flowing north into Imperial Valley and south into Mexico, were independently verified in this study, but data often were not available to independently verify all data used in this study.

10) Page 5, Last Two Paragraphs.
Comment: *Although the mathematical model seems to be providing reasonable results, more sensitivity runs and error budget analysis seems warranted since the magnitude of the effects being sought are small in relation to the size of the input uncertainties. It would be helpful to develop a table similar to Table 6-1 which could present an estimated error budget for each of the named features in the table.*

Response: Note that an error budget was given in Section 8 and the executive summary relating the overall model error to the model predictions. While additional analysis of uncertainty in the model predictions may be justified on technical grounds, Tetra Tech feels that it would require a level of effort well beyond the scope of this study. First, uncertainties in each of the principal components of the observed water budget would have to be quantified. We are prepared to perform only qualitative evaluations of this "input" uncertainty within our scope (see response to comments 6 and 9). Second, a multi-variate statistical analysis using an uncertainty technique such a Monte Carlo simulation would be necessary in order to truly define the relationship between the uncertainty in the model input parameters and uncertainty in the model output. This procedure would require hundreds of model runs and significant post-processing steps.

Such an investigation is well beyond the scope and schedule allocated for this study. While a Monte Carlo uncertainty analysis would be interesting, it is unlikely to change one of the key findings of this study: the change in flows to the Salton Sea and adjacent wetlands are a relatively small component of the overall water balance. Under any reasonable range of variations in the model input parameters and assumptions, changes in flows to the Salton Sea and adjacent wetlands are likely to still be a relatively small component of the overall water balance. Therefore, there may be relatively little to gain from this exercise which would be costly in terms of both time and resources.

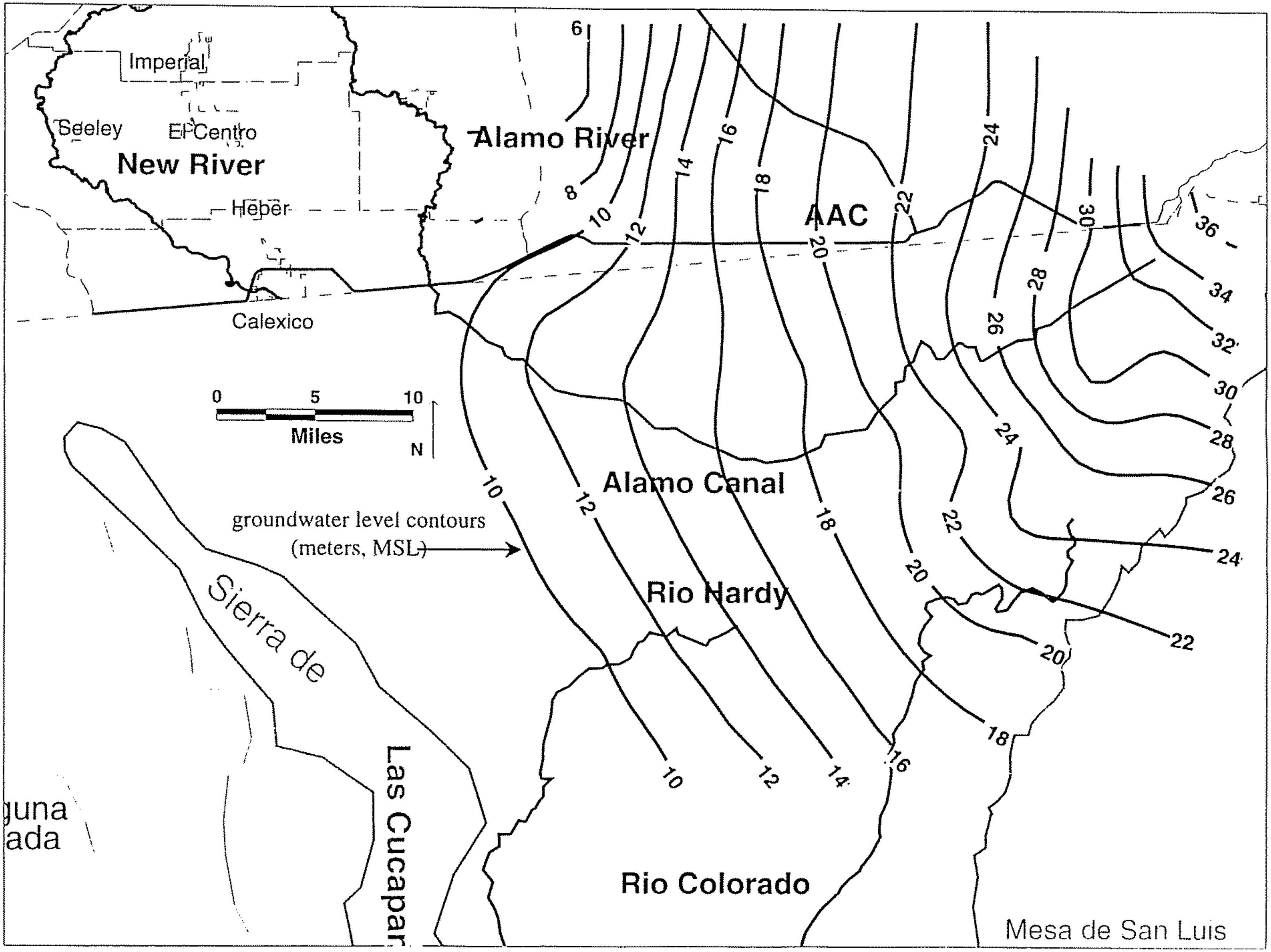
11) Page 6, First Paragraph.
Comment: *Because of the uncertainty of the accuracy of the water budget item, the values should be rounded to the nearest 1,000 acre-feet. This is particularly true of the model predicted values.*

Response: The uncertainty in key items is noted in the executive summary and Section 8. Tables will also be modified indicating that the number of significant digits does not necessarily reflect the precision of the number; Tetra Tech prefers not to round the tabular values because the tables would lose the direct correlation with the model output, which has even more than four or five significant digits.

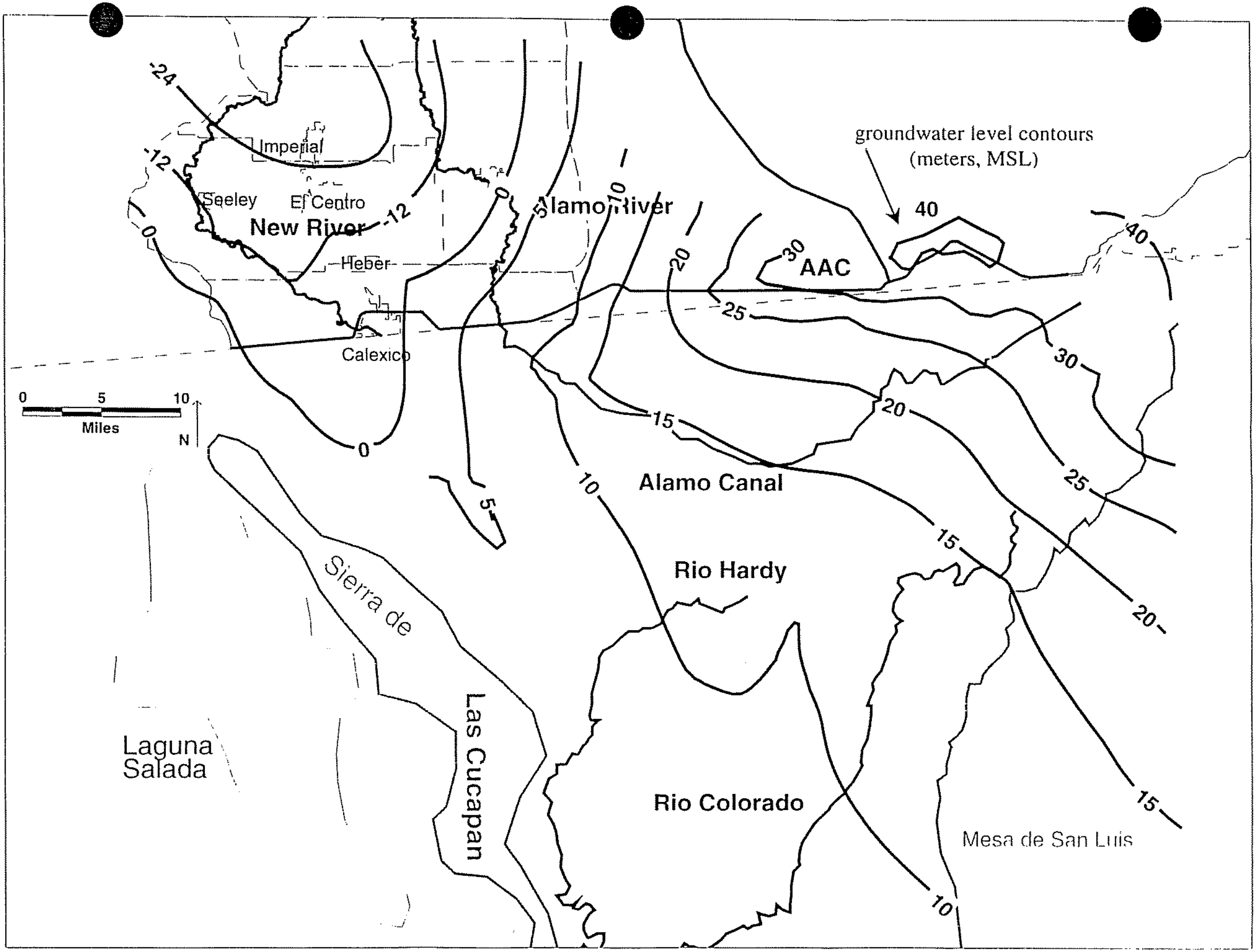
12) Page 6, Last Paragraph.
Comment: *Investigation on the suitability of the 1 in. galvanized pipes for use in model calibration should be justified with reference to the point and average head concept as discussed above.*

Response: Text will be added indicating that 1-inch galvanized pipes measure specific points rather than average aquifer heads, which may introduce measurement errors of several feet. However, since this model is regional in scope, and calibration seeks to match heads within 10 feet, the error associated with point rather than average aquifer head measurements should be reasonable for this investigation.

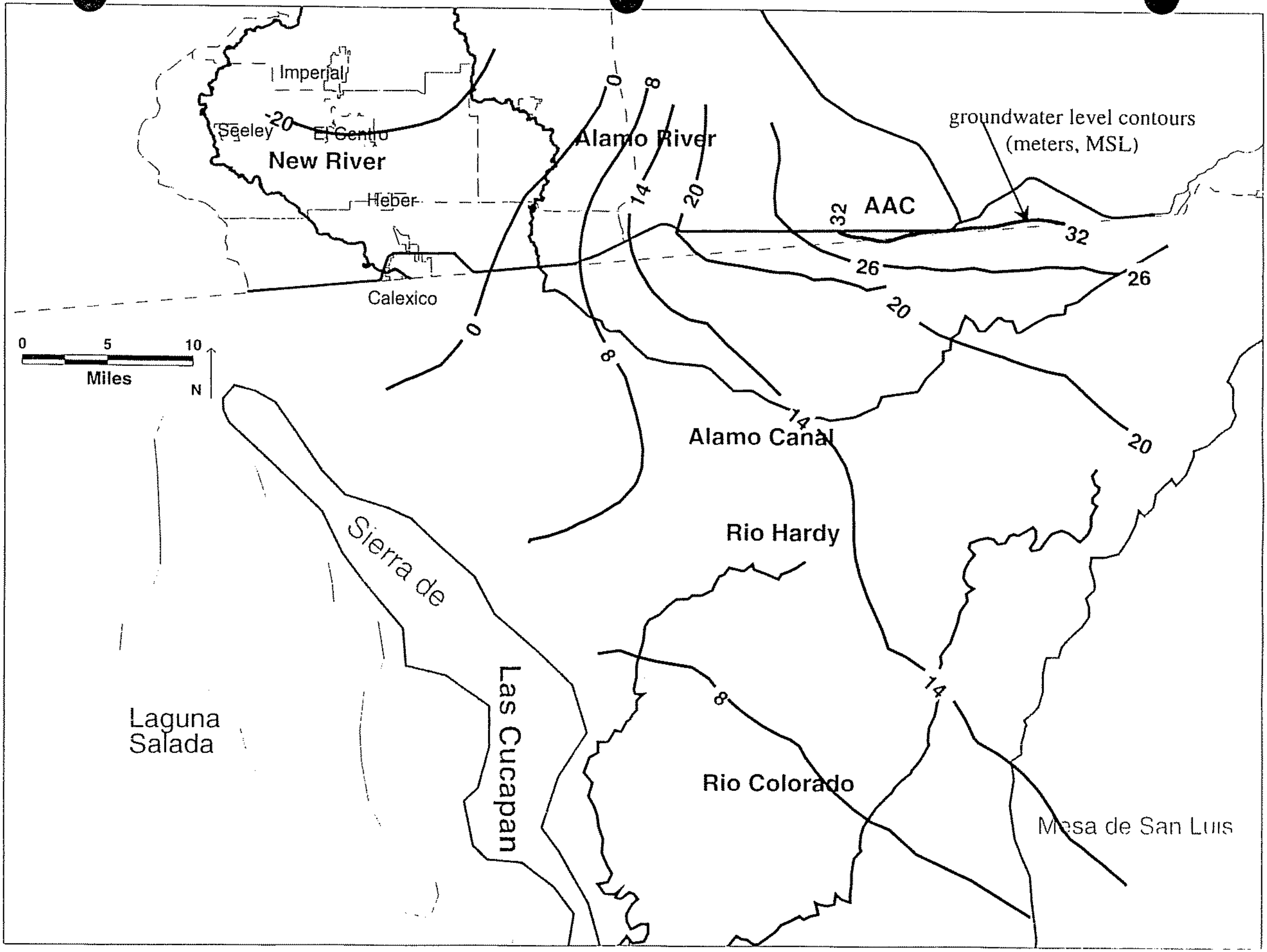
APPENDIX E WATER LEVEL DATA FOR STUDY AREA



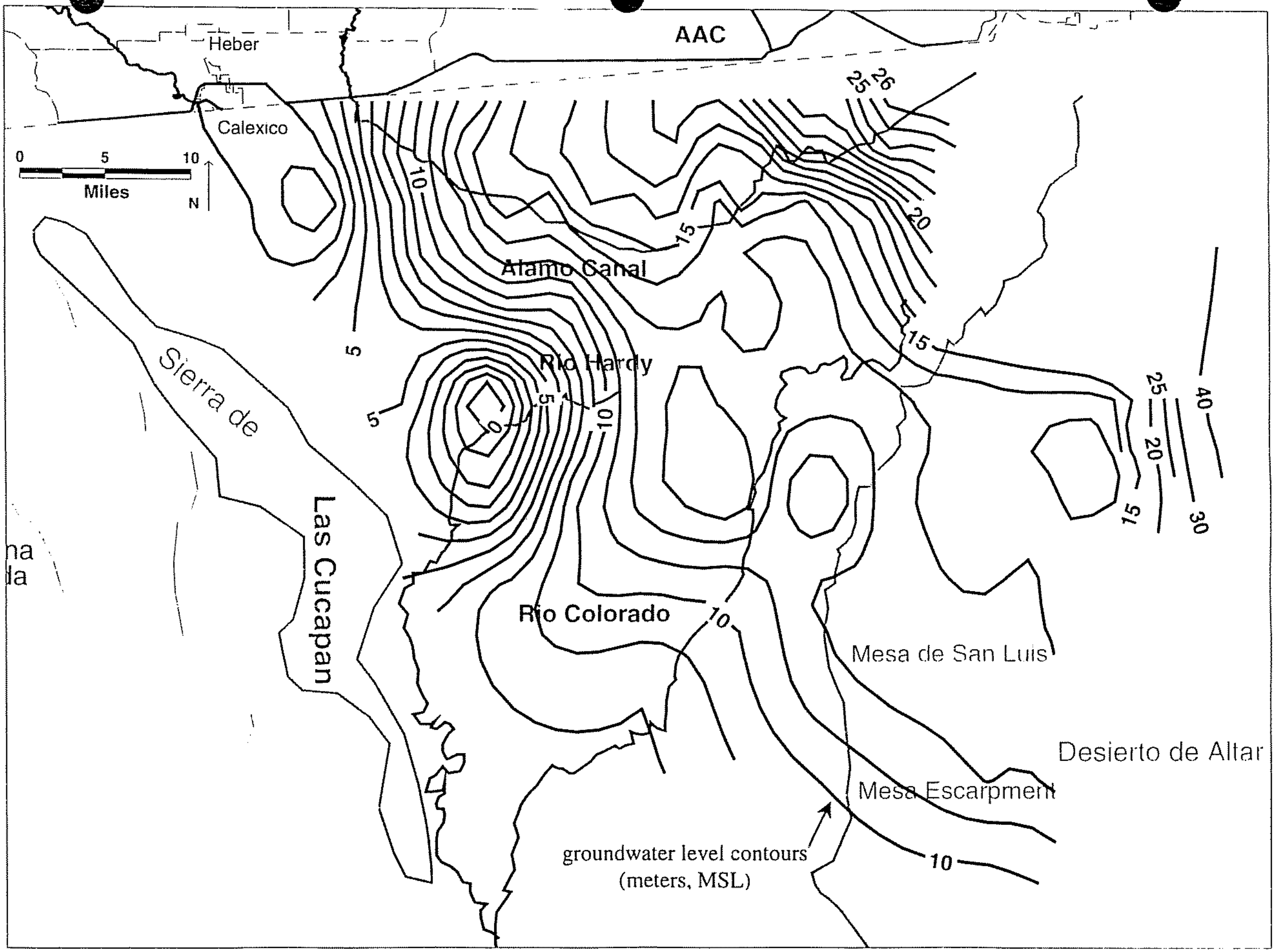
Mexicali Valley Groundwater Level Contour Map for 1939 (Source:USBR, 1991)



Mexicali Valley Groundwater Level Contour Map for 1985 (Source:USBR, 1991)

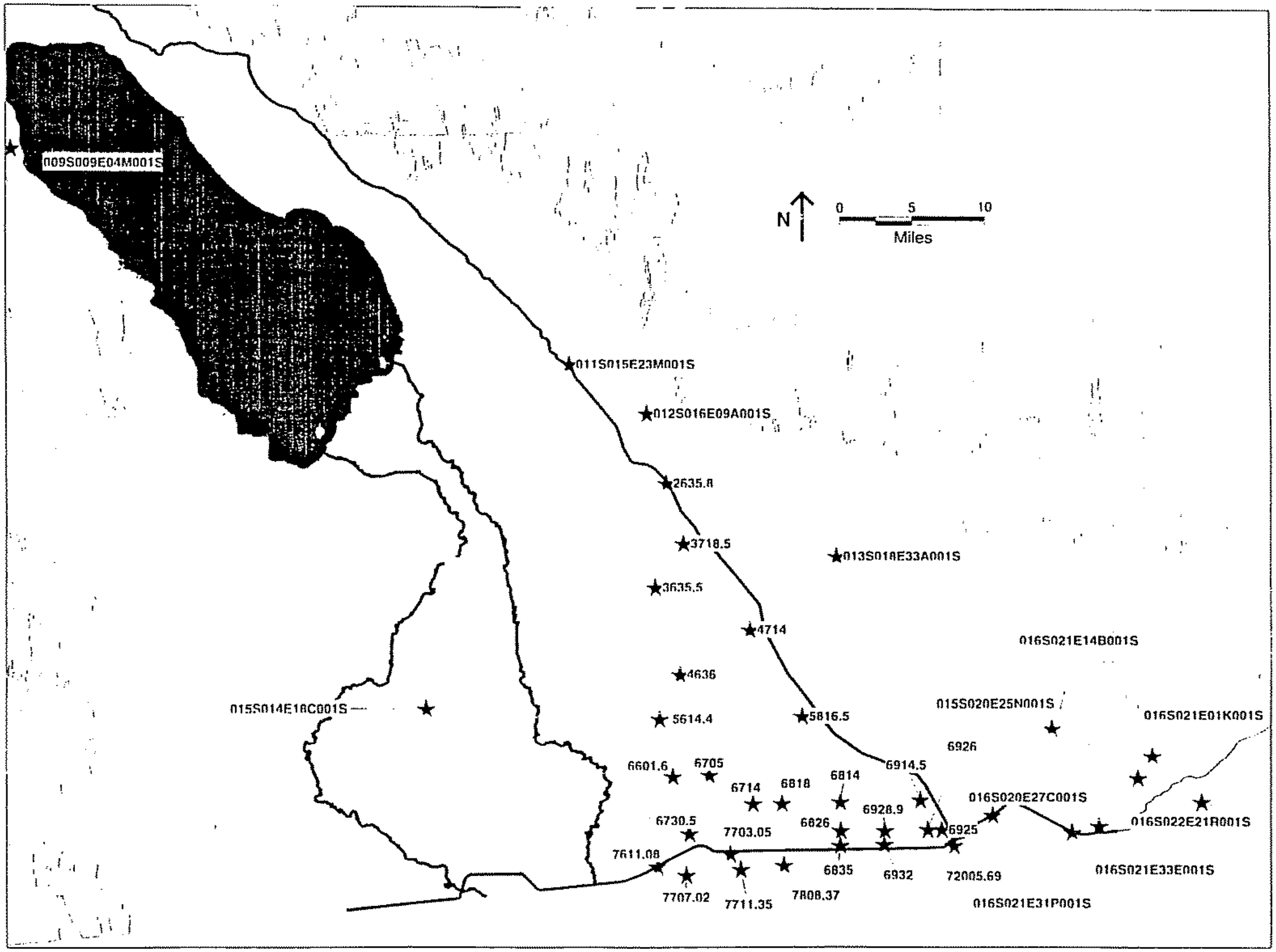


Mexicali Valley Groundwater Level Contour Map for 1989 (Source:USBR, 1991)



Mexicali Valley Groundwater Level Contour Map for 1993 (Source:USBR, 1991)

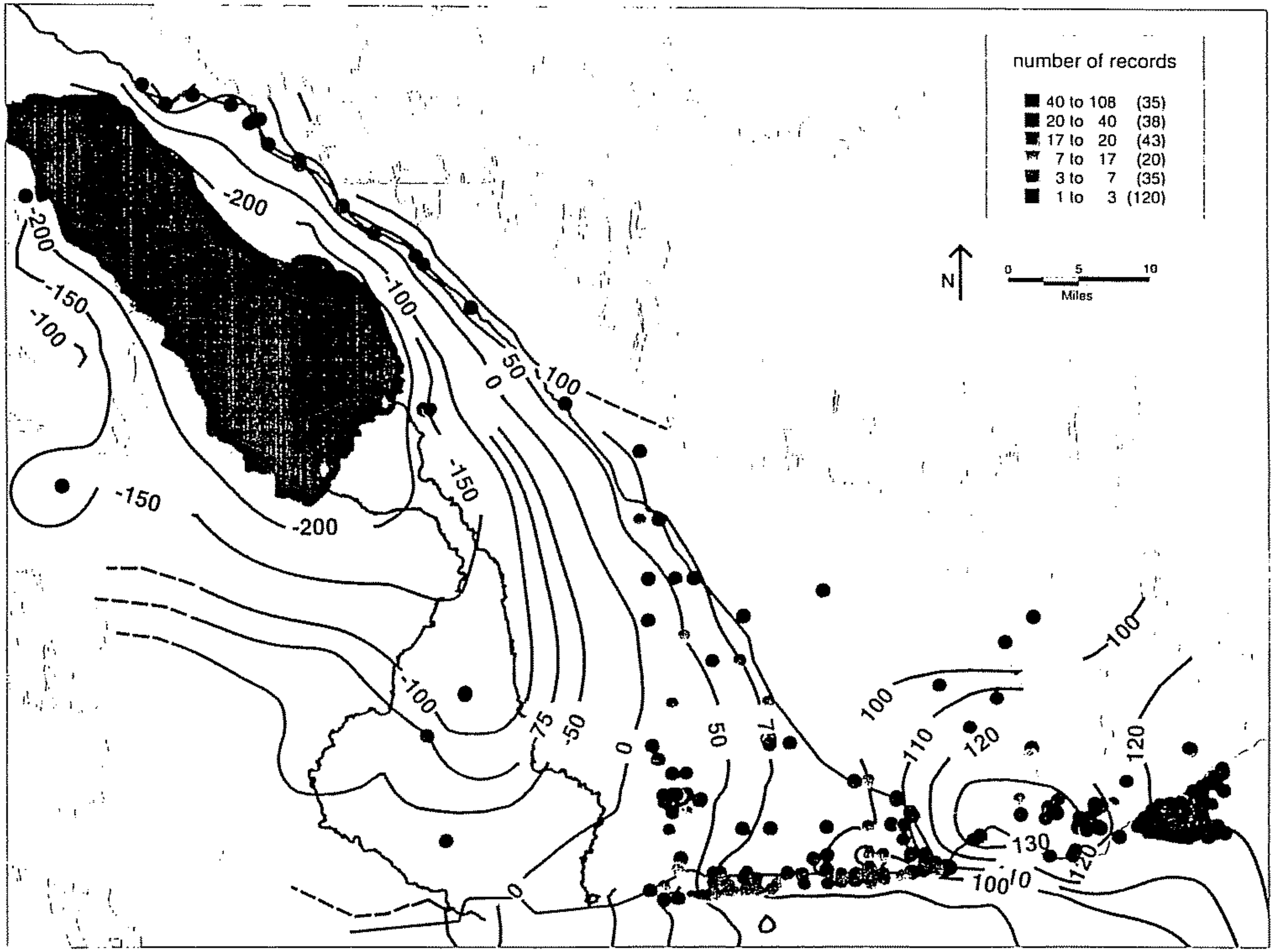
Wells selected for transient calibration period



Well locations selected for transient model calibration between 1979 and 1998

SSA

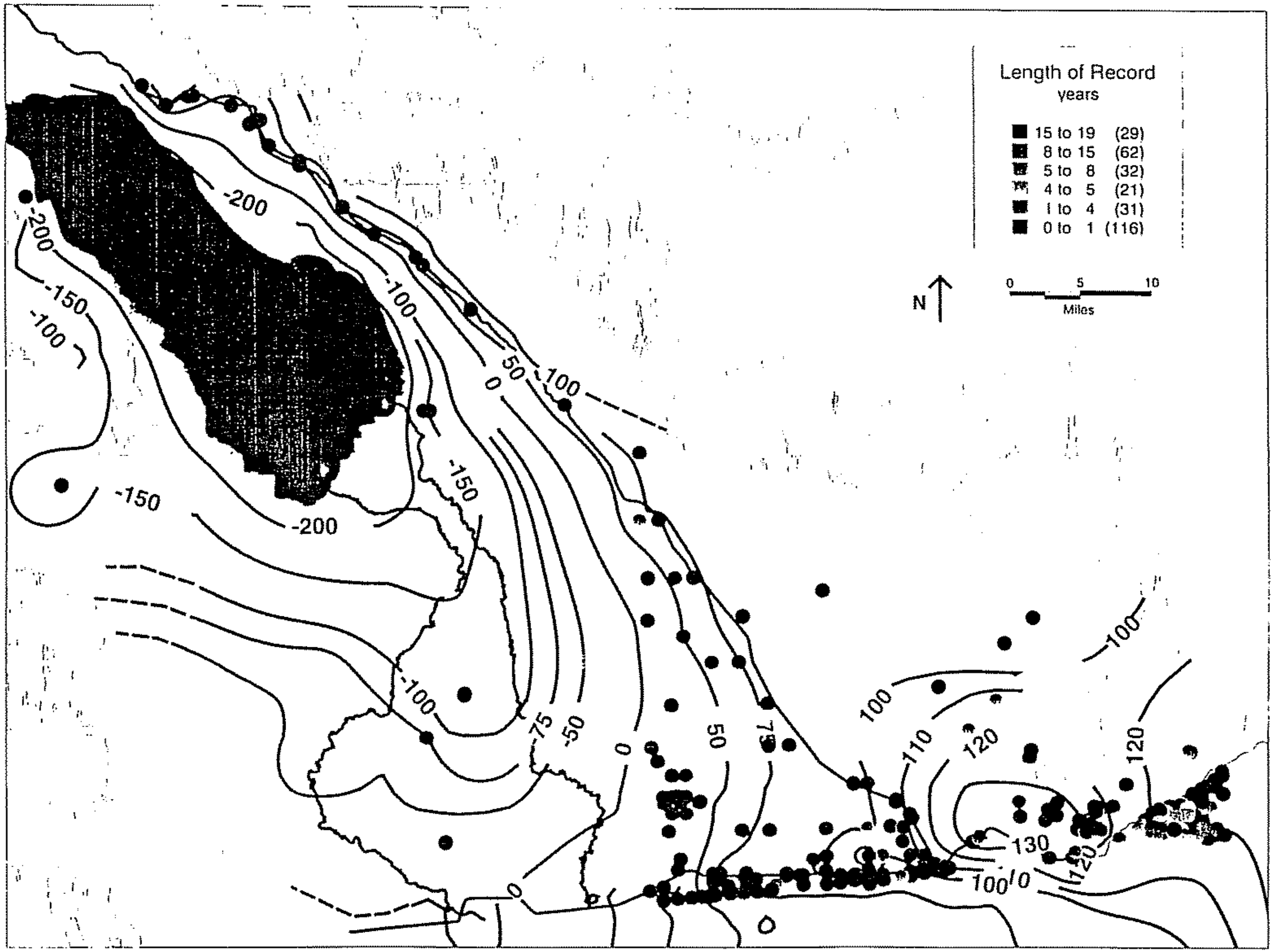
Number of water levels during transient calibration period



Number of water level measurements per well between 1979 and 1998

SSA

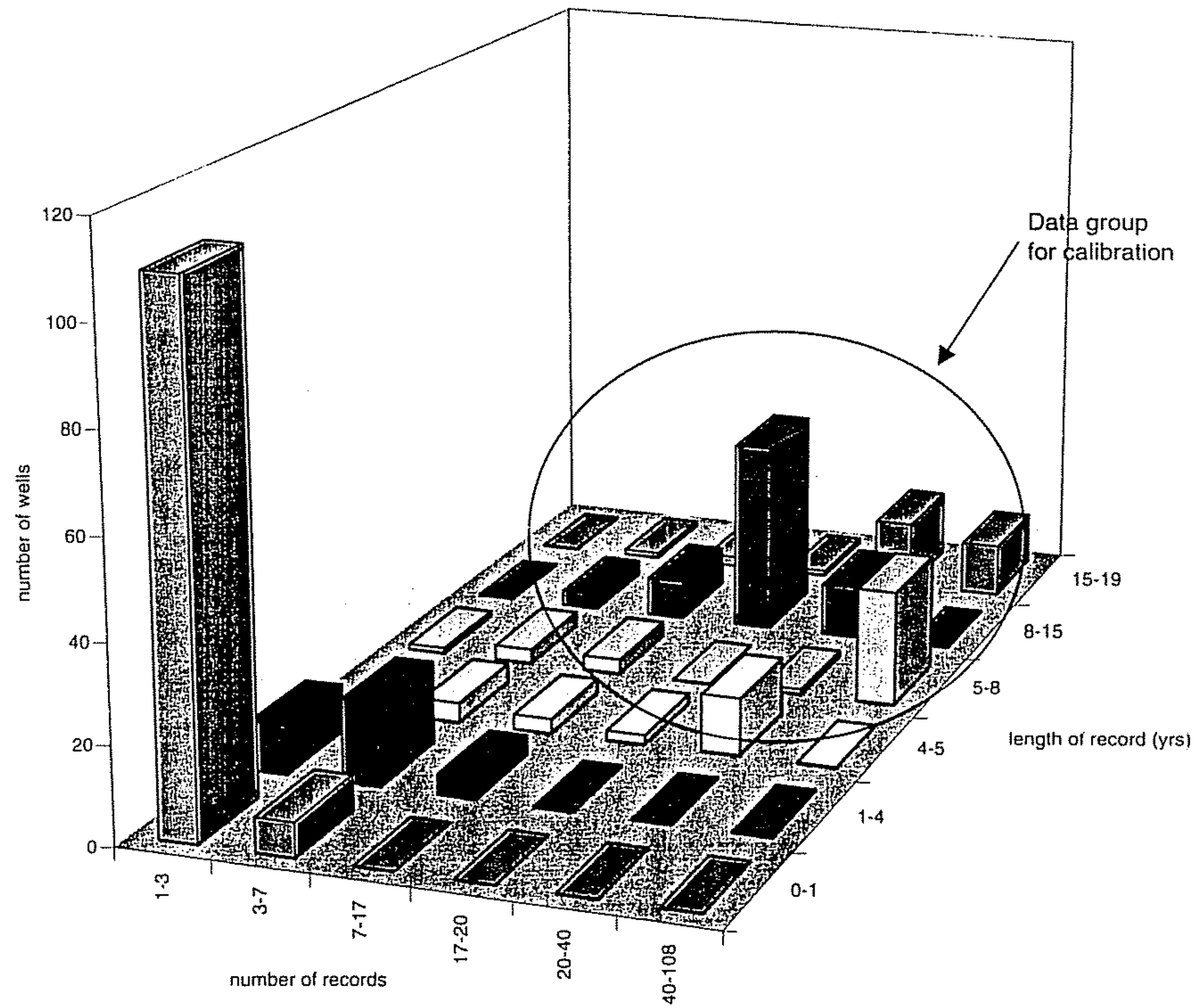
Water level record length during transient calibration period



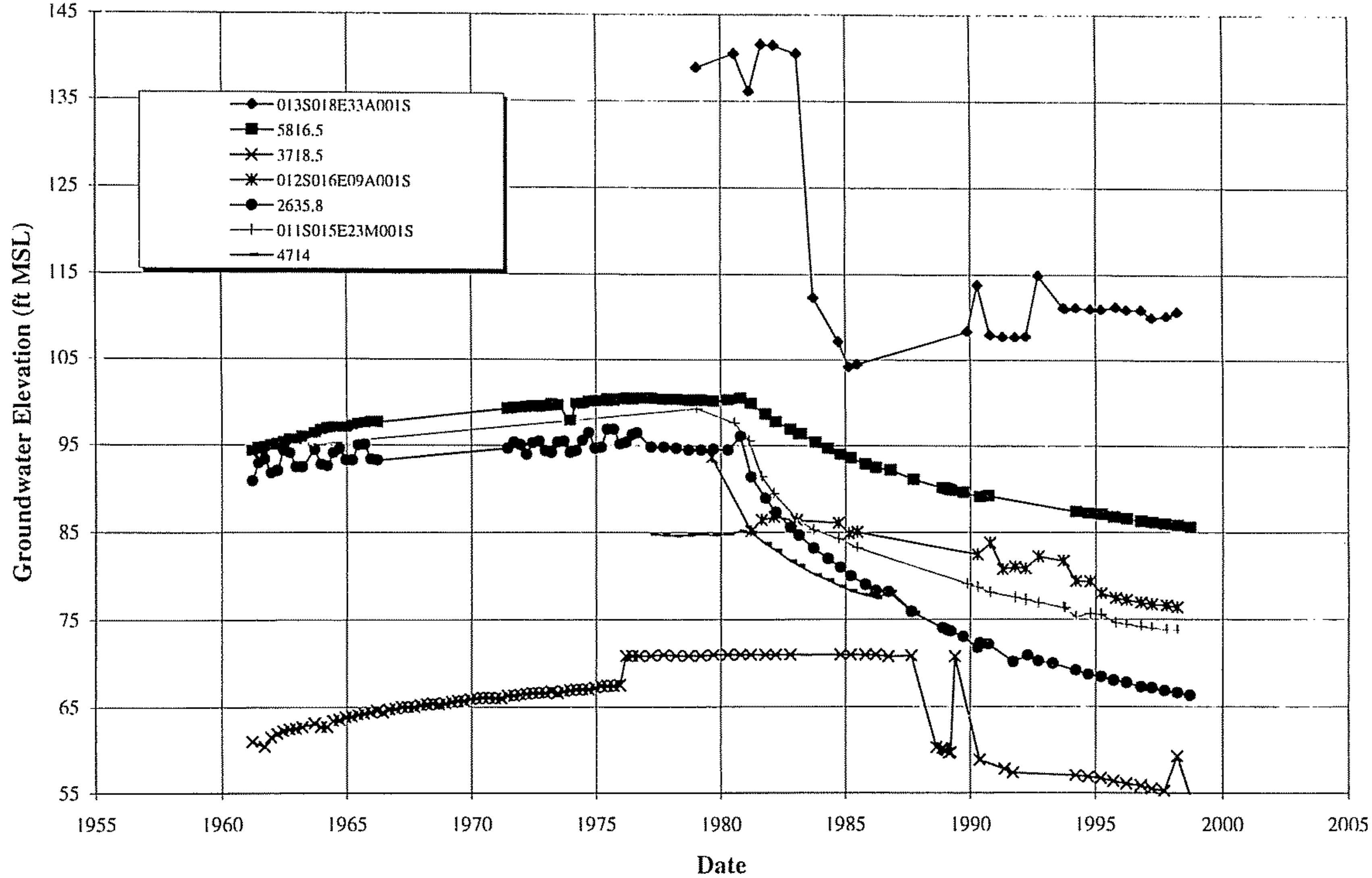
Number of years of water level measurements in each well between 1979 and 1998

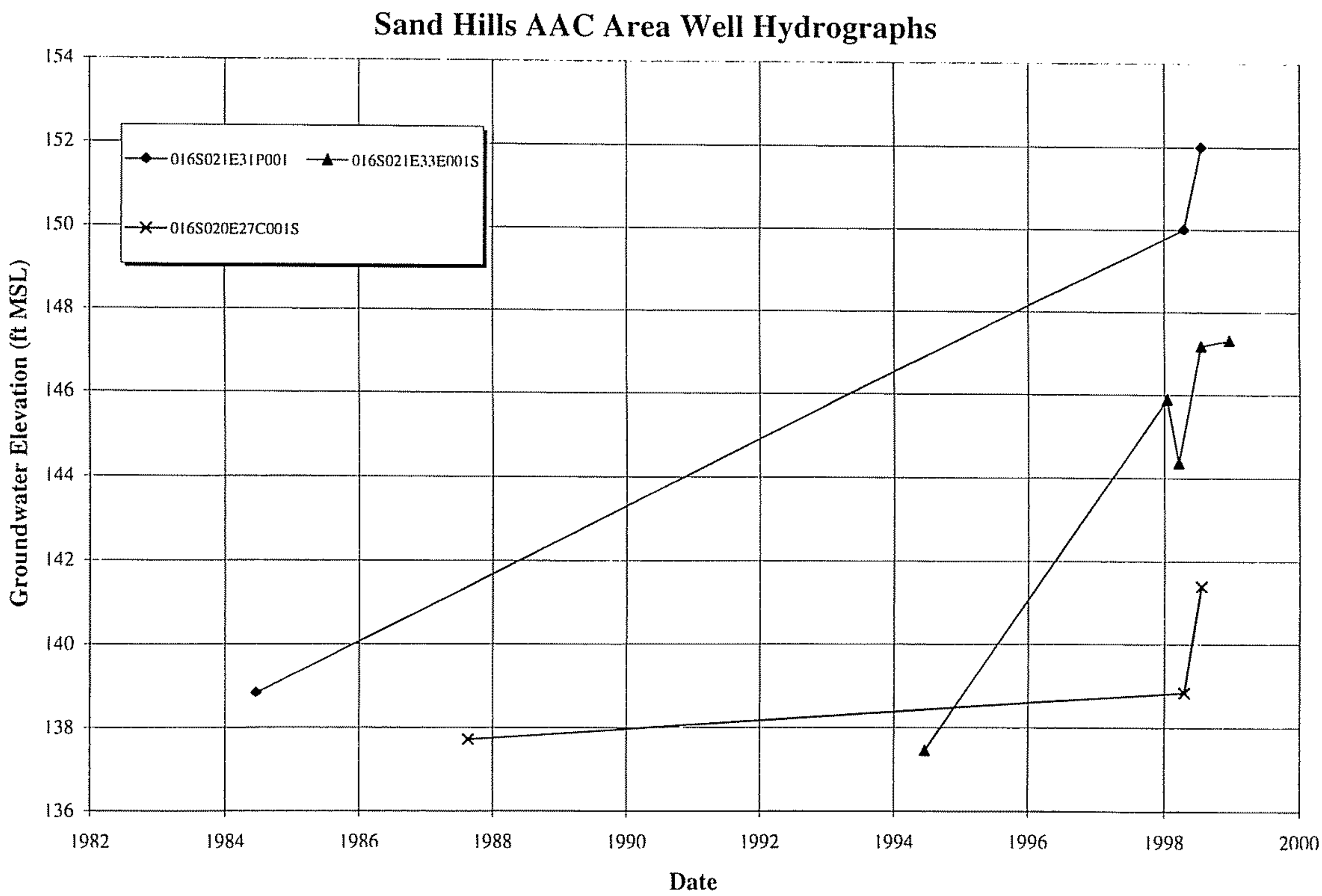
SSA

1979 to 1998 Water Level Data

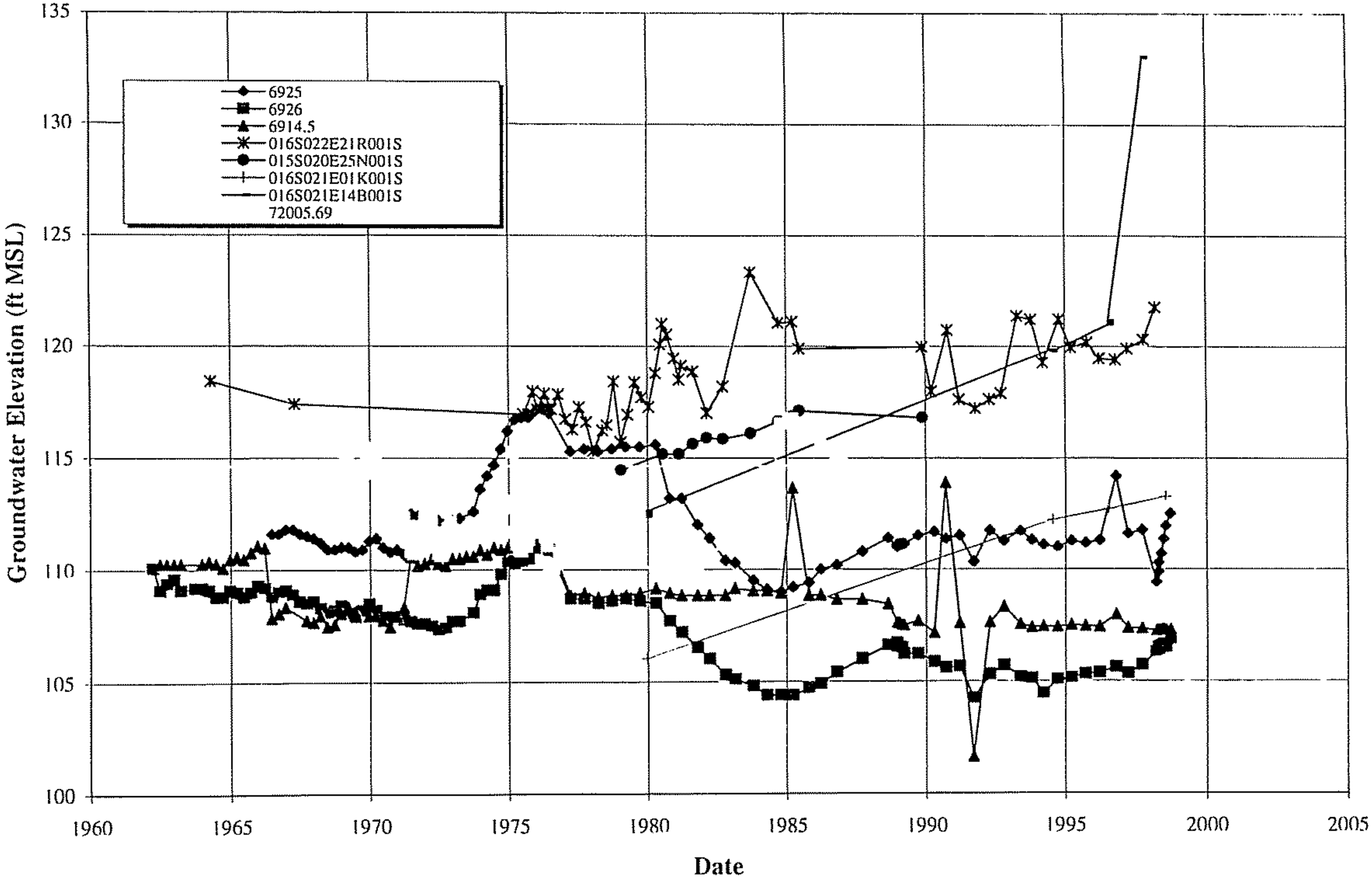


CB Area Well Hydrographs

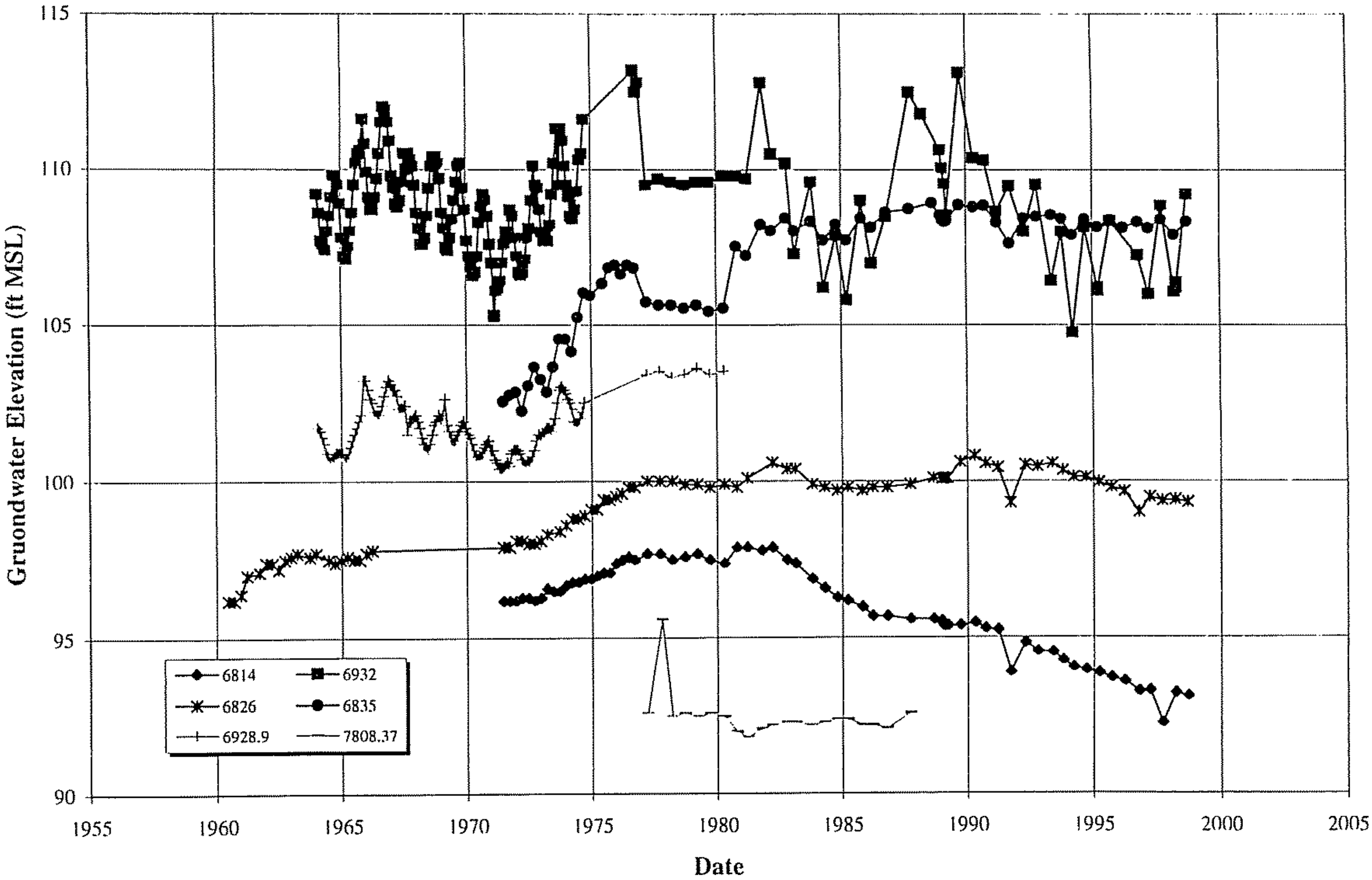



Sand Hills AAC Area Well Hydrographs
016S021E31P001
016S021E33E001S
016S020E27C001S
Groundwater Elevation (ft MSL)
154
152
150
148
146
144
142
140
138
136
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
Date

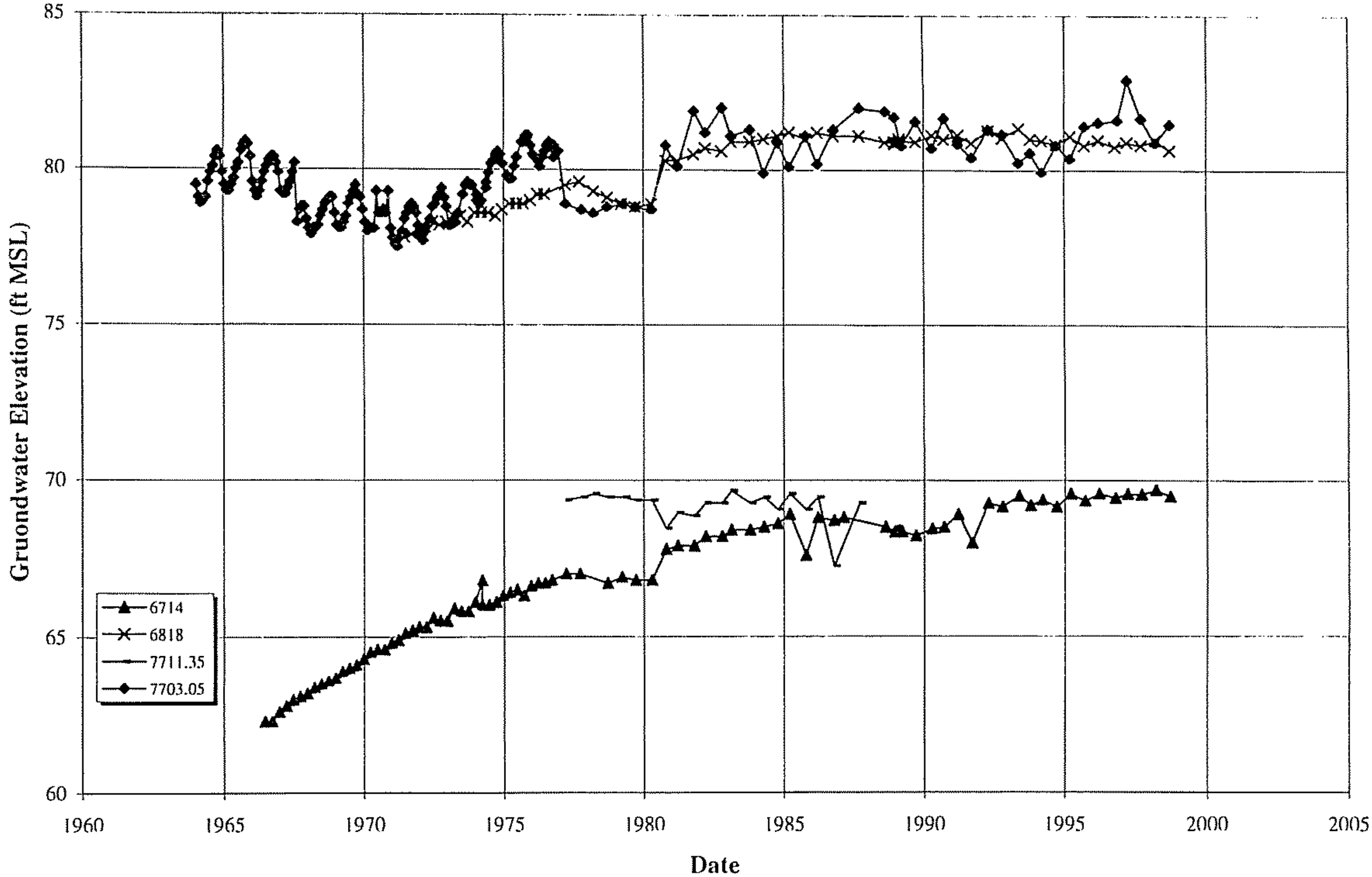
Sand Hills CB Turnout Area Well Hydrographs



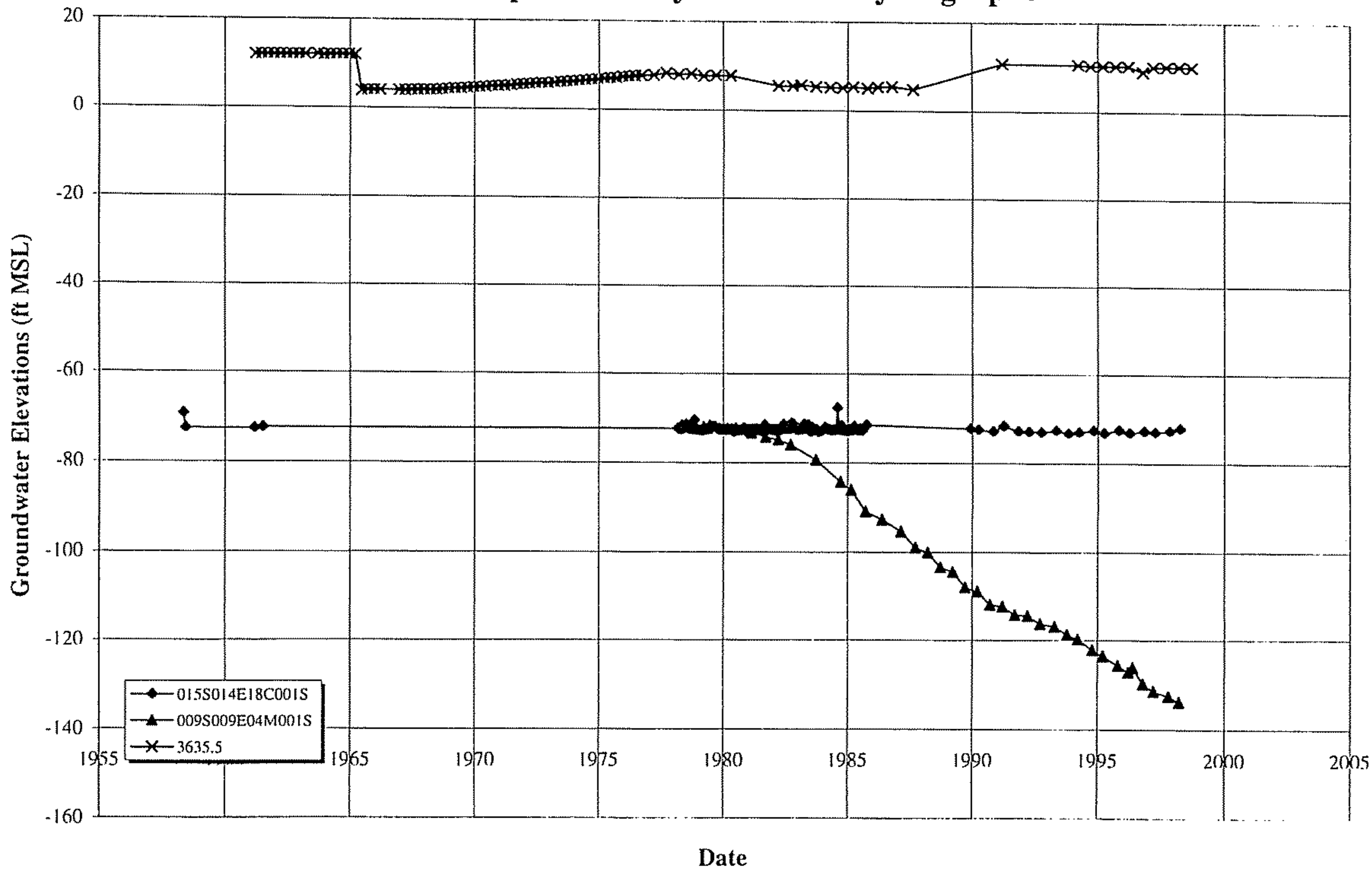
East Mesa - AAC Drop 2 Area Well Hydrographs

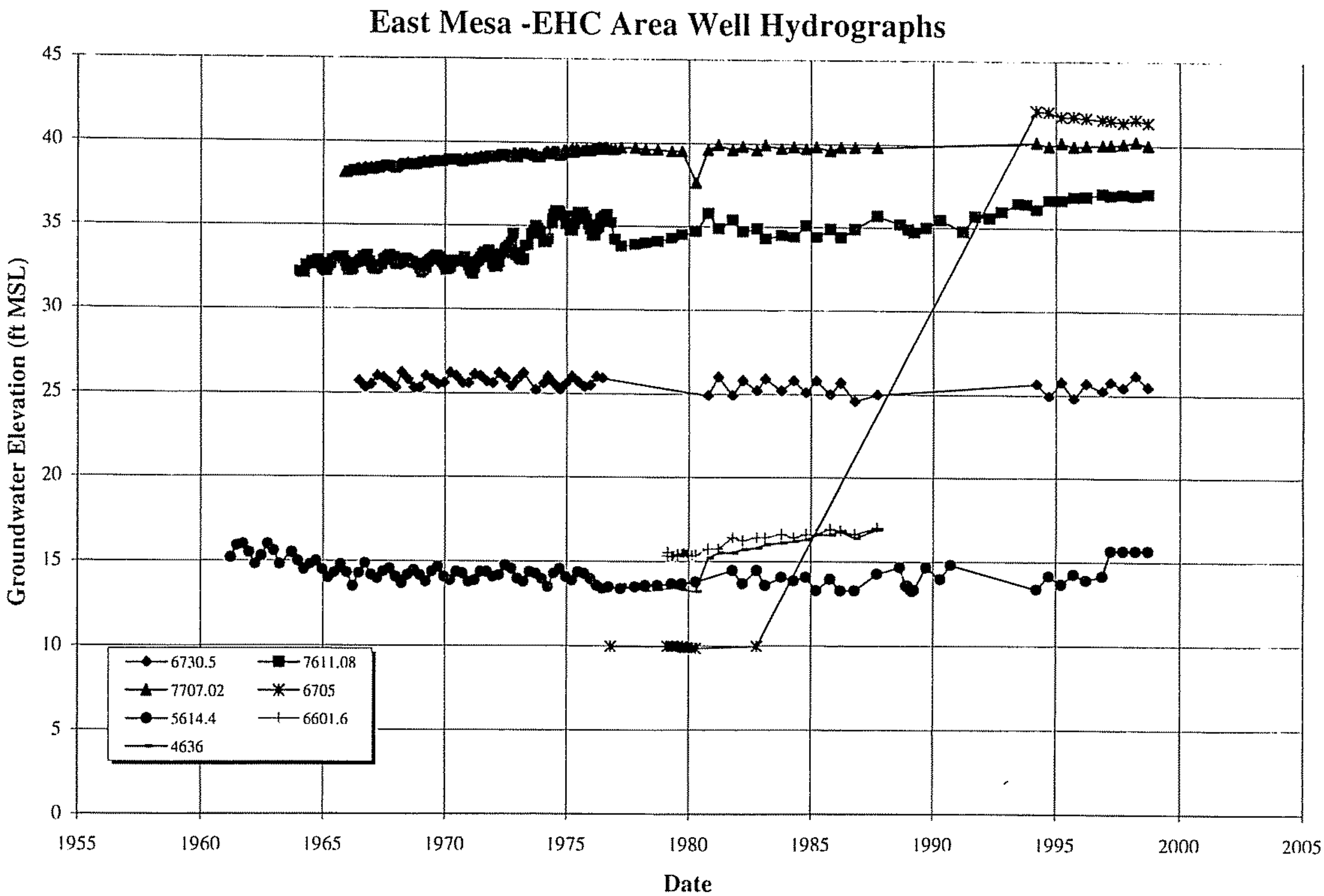


East Mesa - AAC Drop 4 Area Well Hydrographs



Central Imperial Valley Area Well Hydrographs




East Mesa -EHC Area Well Hydrographs
Groundwater Elevation (ft MSL)
Date
45
40
35
30
25
20
15
10
5
0
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
6730.5
7611.08
7707.02
6705
5614.4
6601.6
4636

APPENDIX F AQUIFER AND AQUITARD TOPOGRAPHIC MAPS

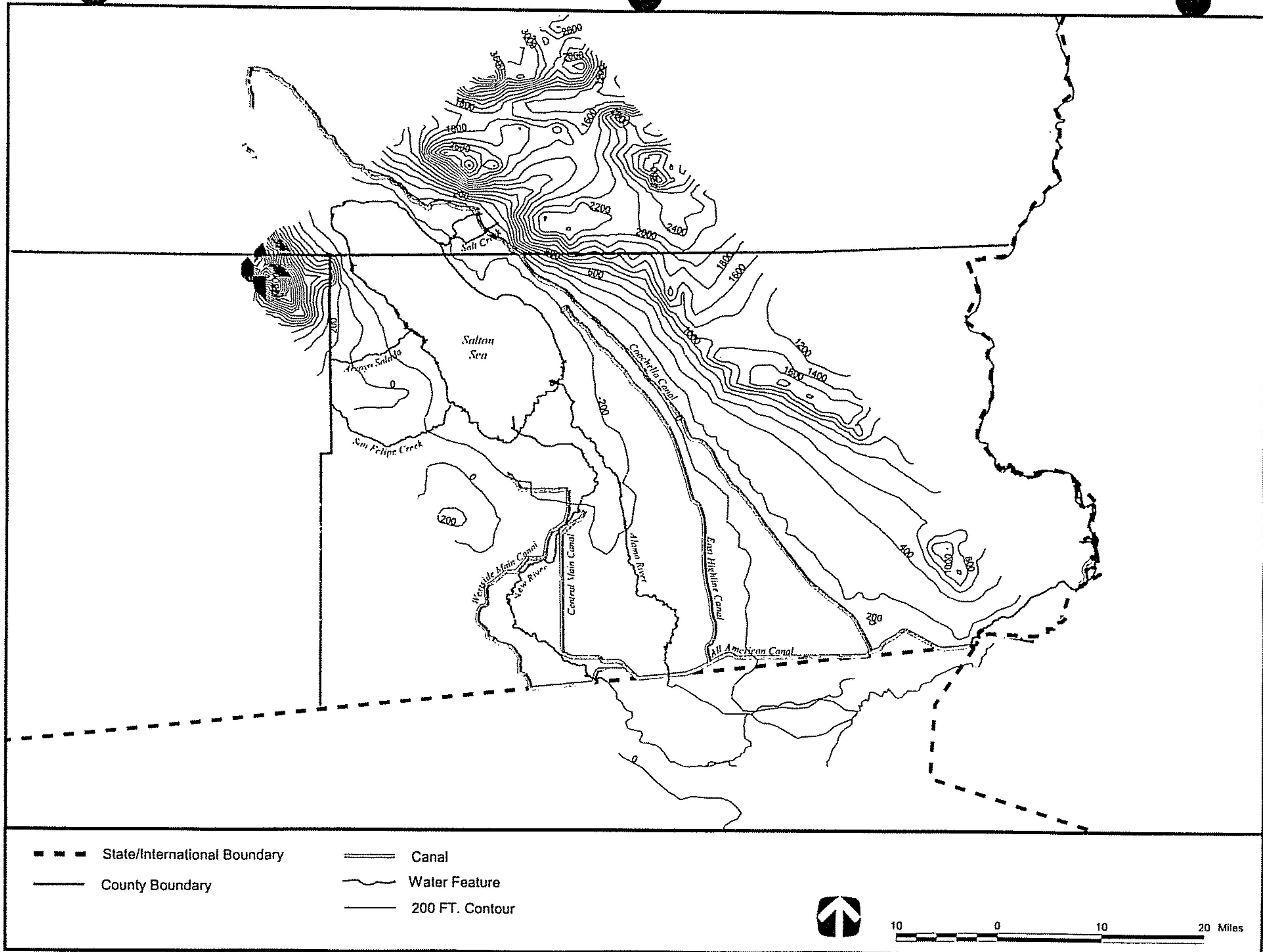


Figure F-1 Top of Layer 1 - Tetra Tech Model

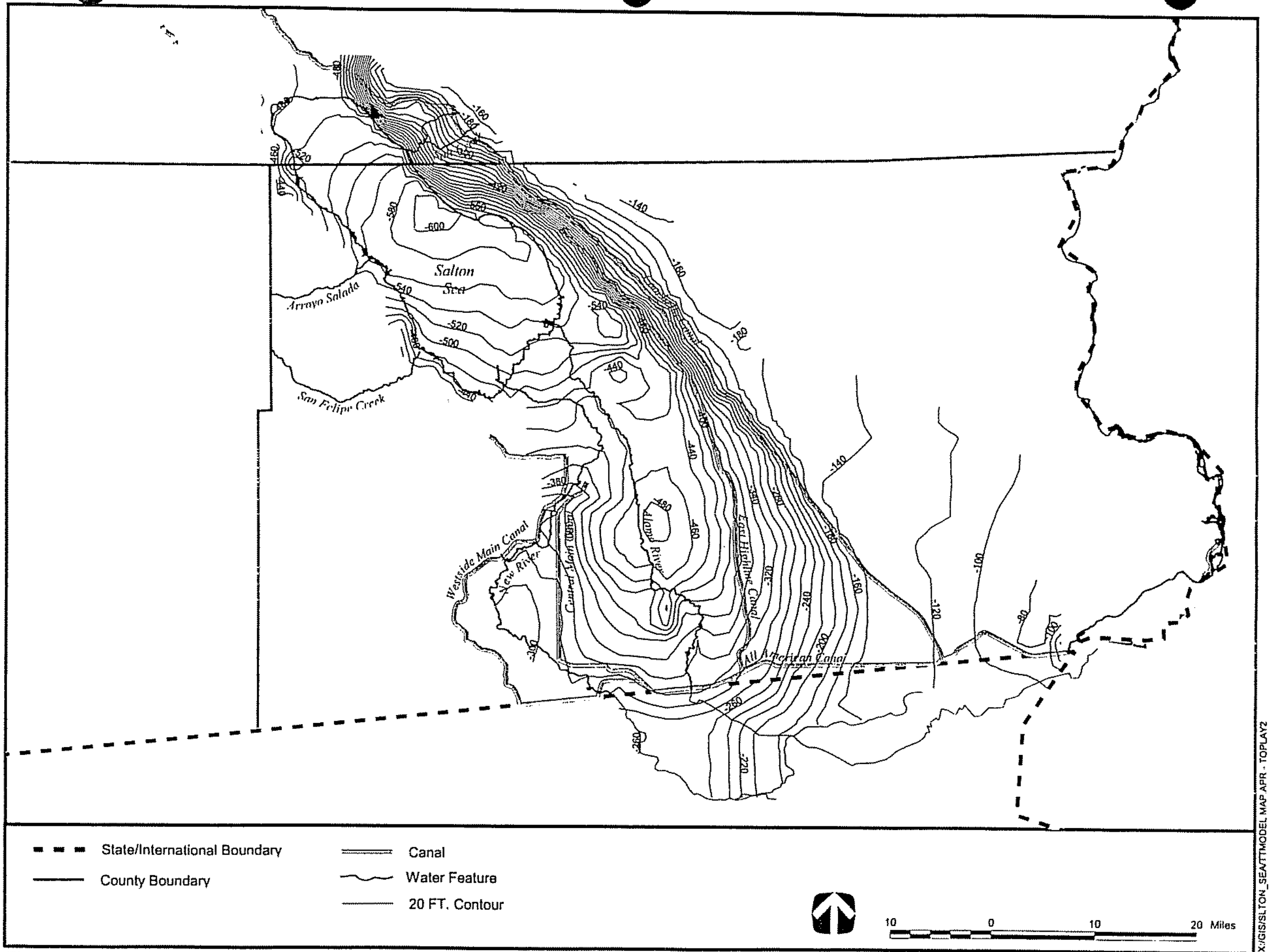


Figure F-2 Top of Layer 2 - Tetra Tech Model

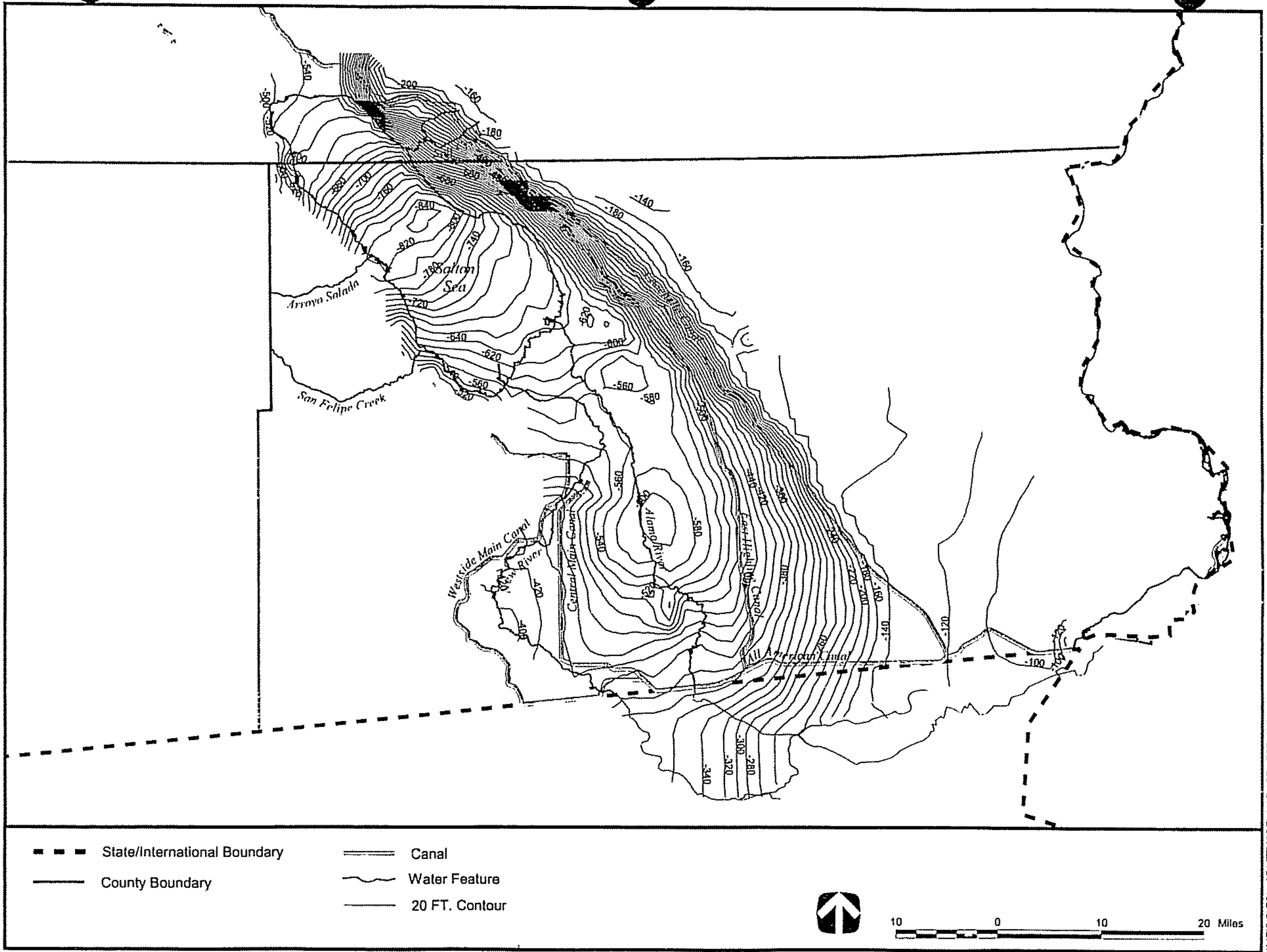


Figure F-3 Top of Layer 3 - Tetra Tech Model

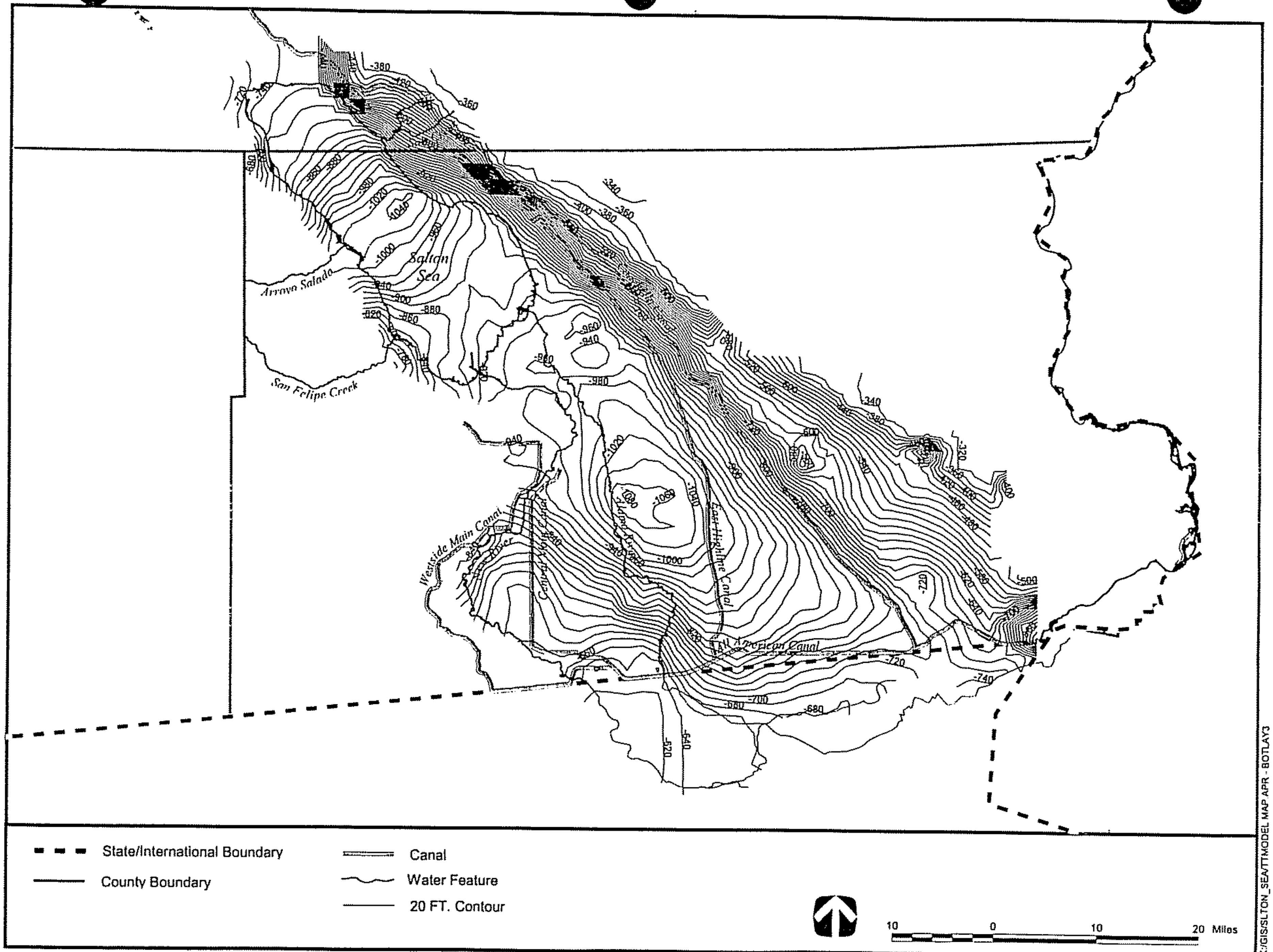


Figure F-4 Bottom of Layer 3 - Tetra Tech Model

APPENDIX G CROSS-SECTIONS AND GEOLOGIC MAP ALONG THE CB

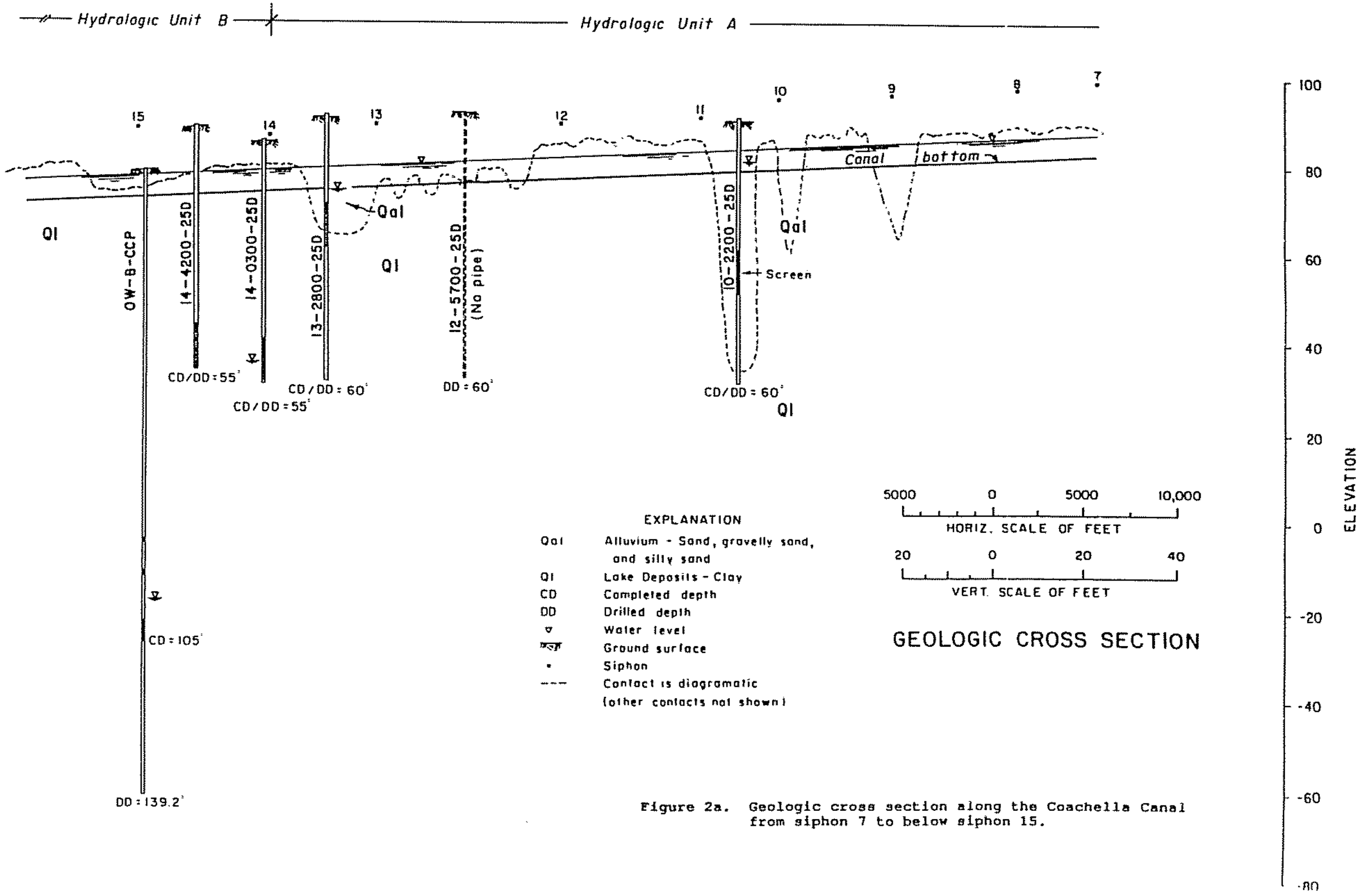


Figure 2a. Geologic cross section along the Coachella Canal from siphon 7 to below siphon 15.

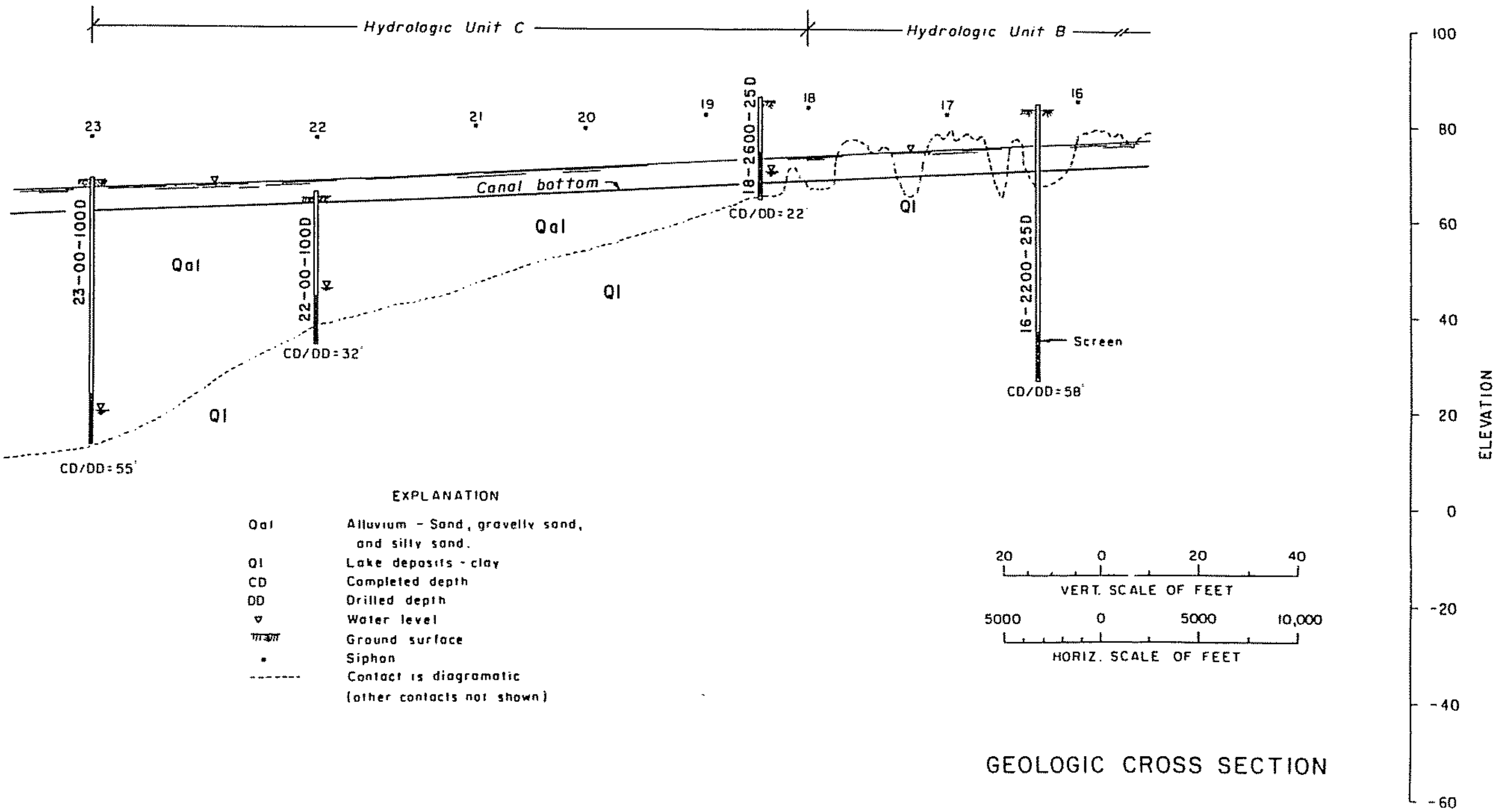


Figure 2b. Geologic cross section along the Coachella Canal from below siphon 15 to below siphon 23.

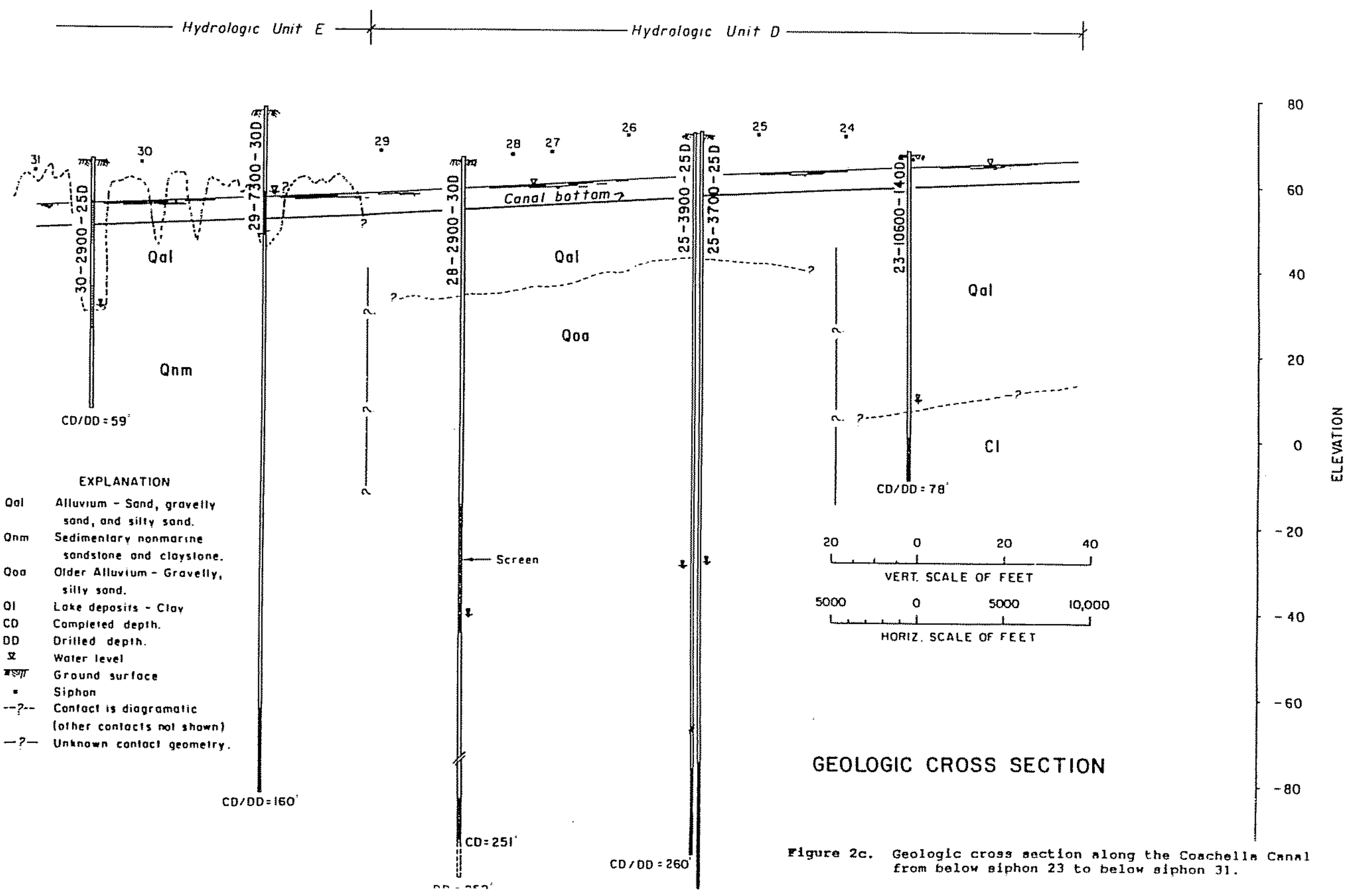
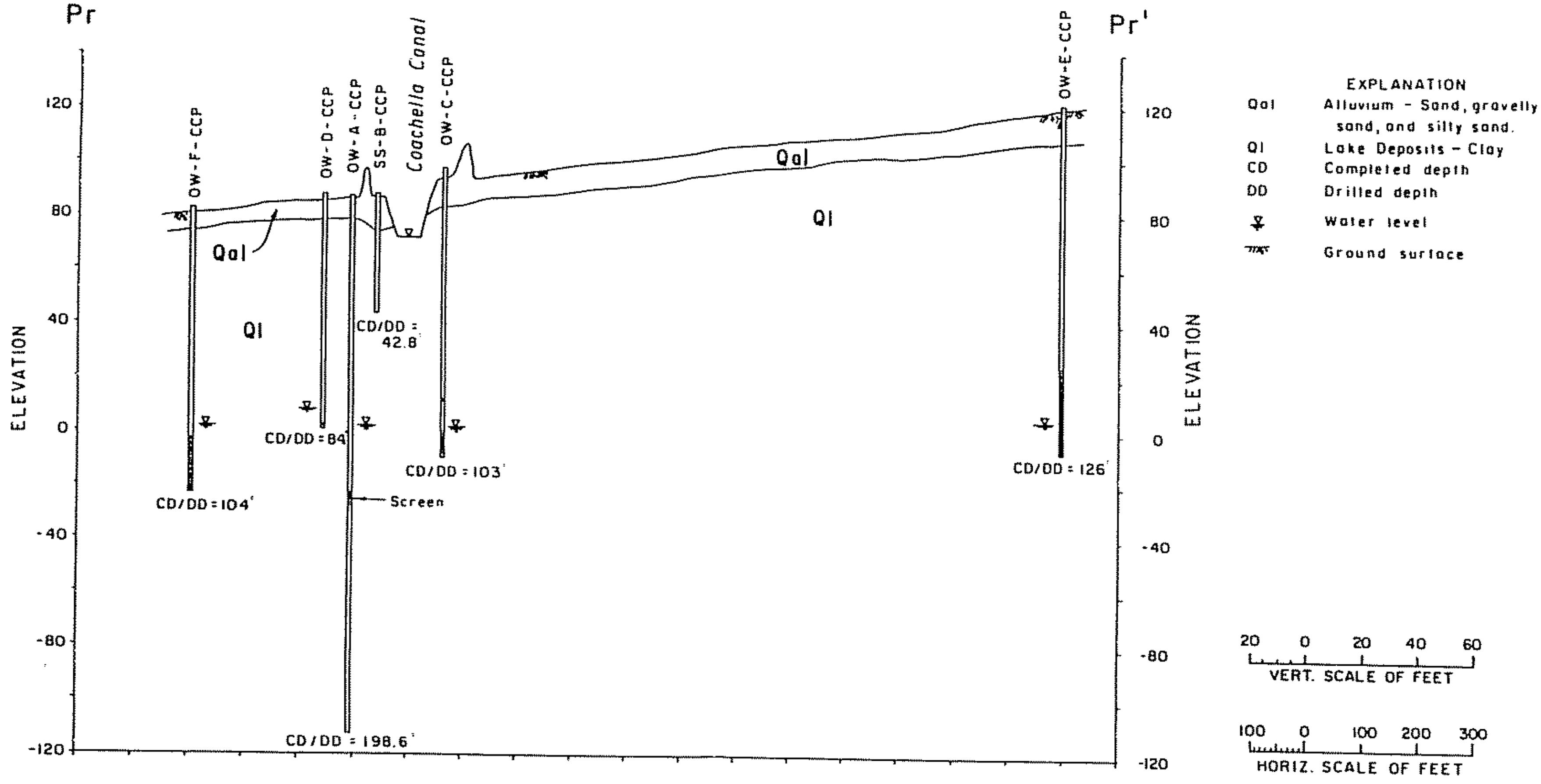


Figure 2c. Geologic cross section along the Coachella Canal from below siphon 23 to below siphon 31.



GEOLOGIC CROSS SECTION Pr-Pr'

Figure 4. Geologic cross section (Pr-Pr') a[illegible]ximately normal to the Coachella Canal be[illegible] siphons 14 and 15.

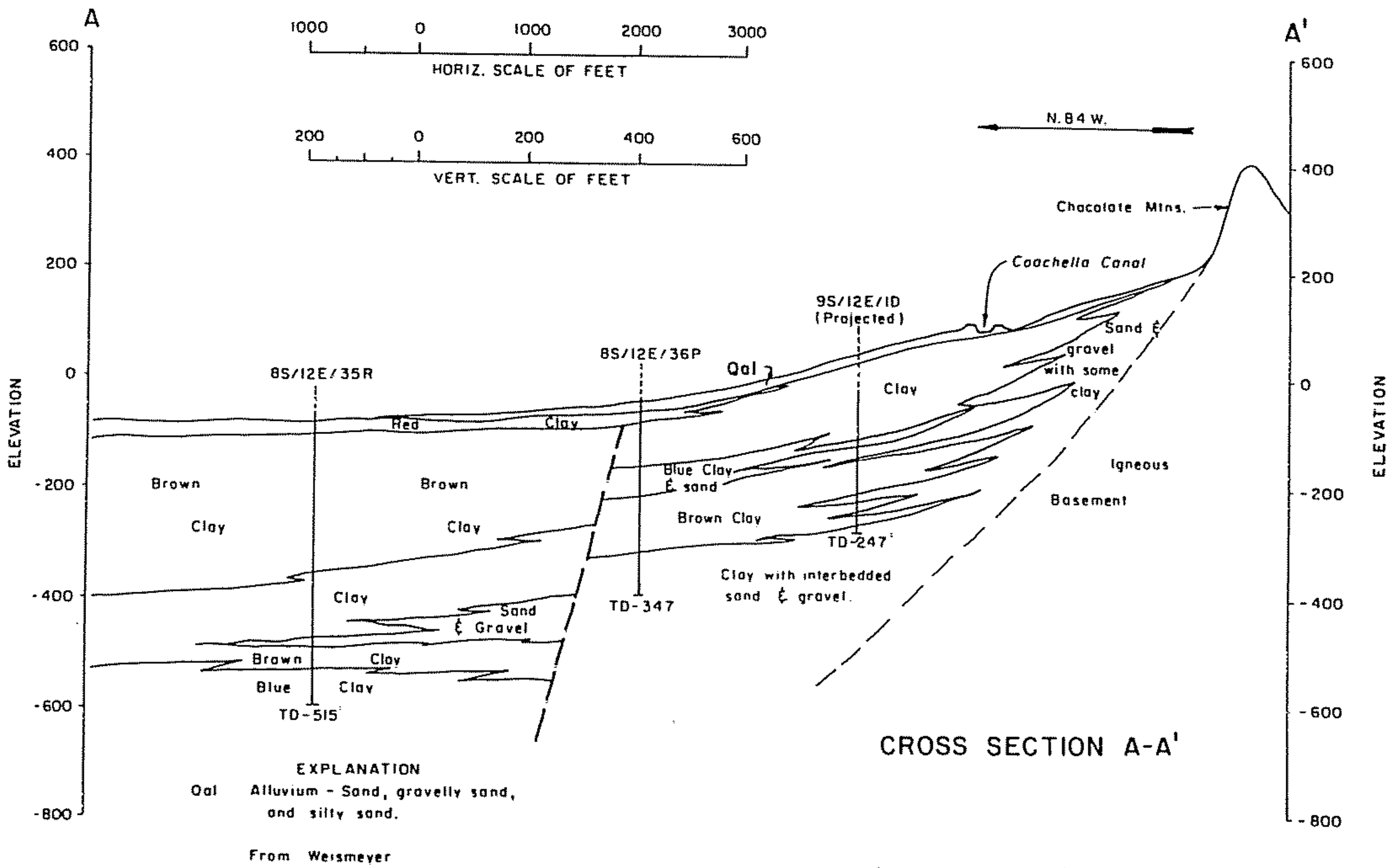


Figure 5. Geologic cross section (A-A') crossing Coachella Canal at approximately 45 degrees near siphon 20. From Weismeyer.

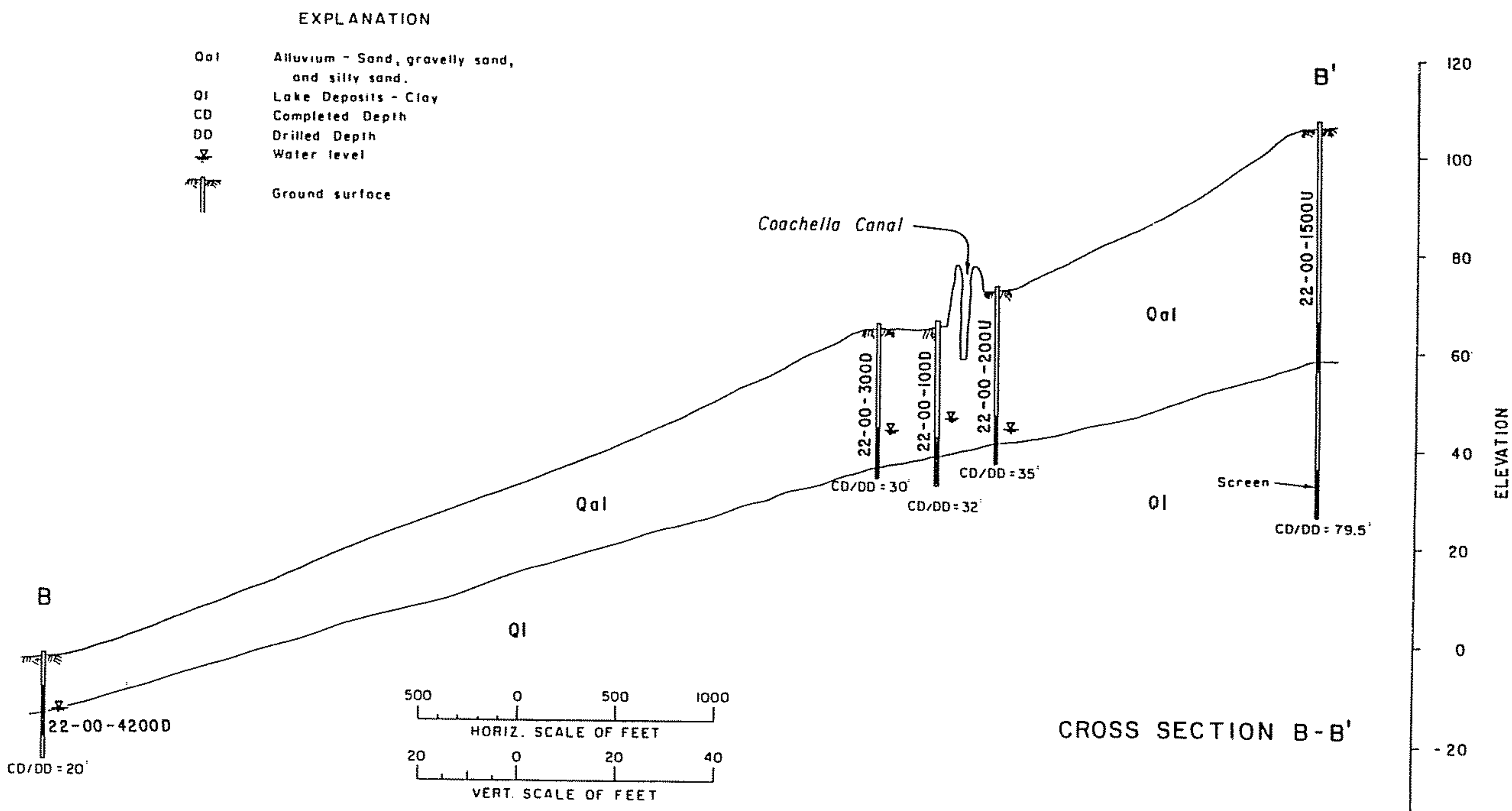


Figure 6. Geologic cross section (B-B') crossing Coachella Canal at approximately 60 degrees at siphon 22.

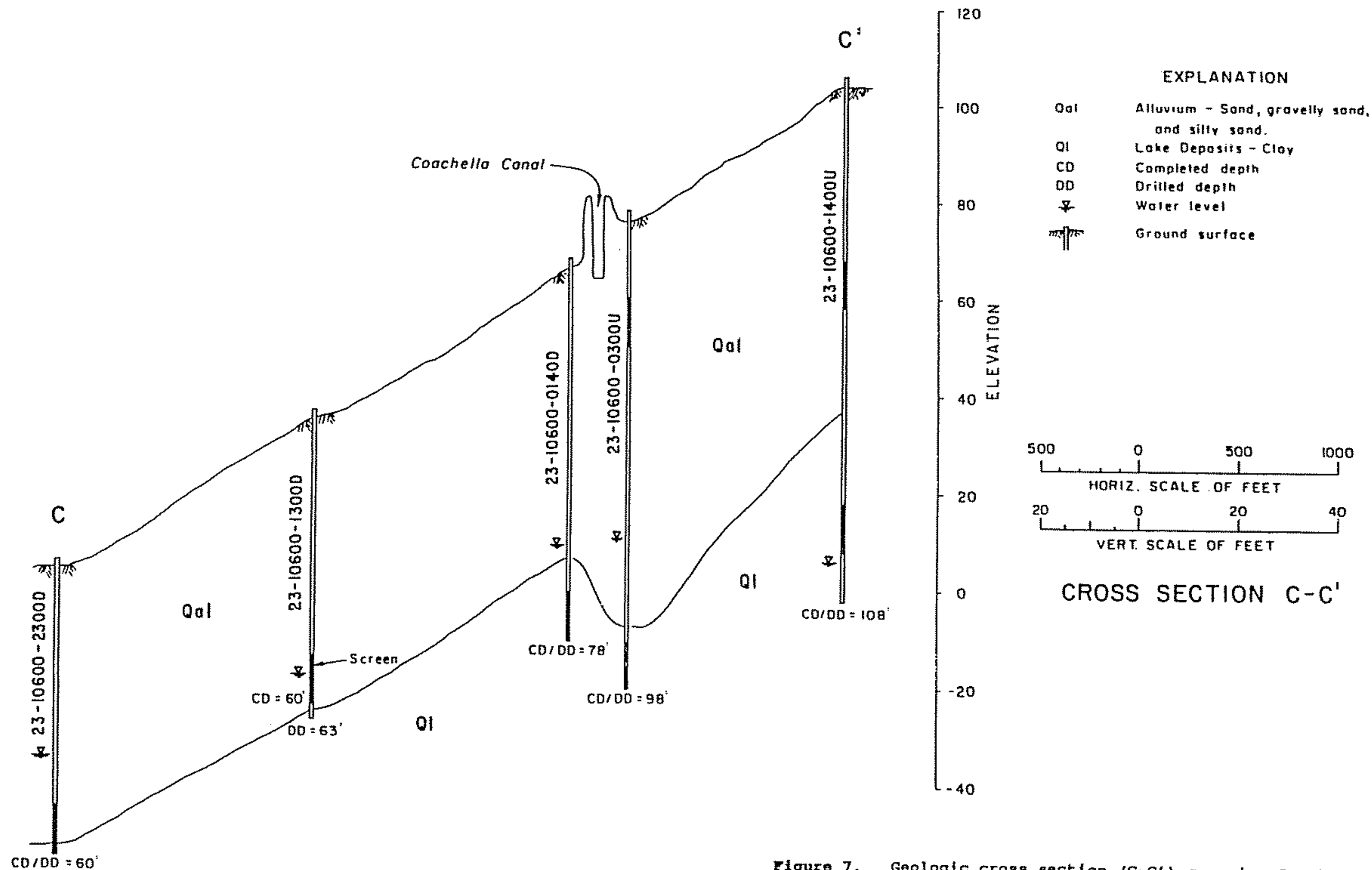
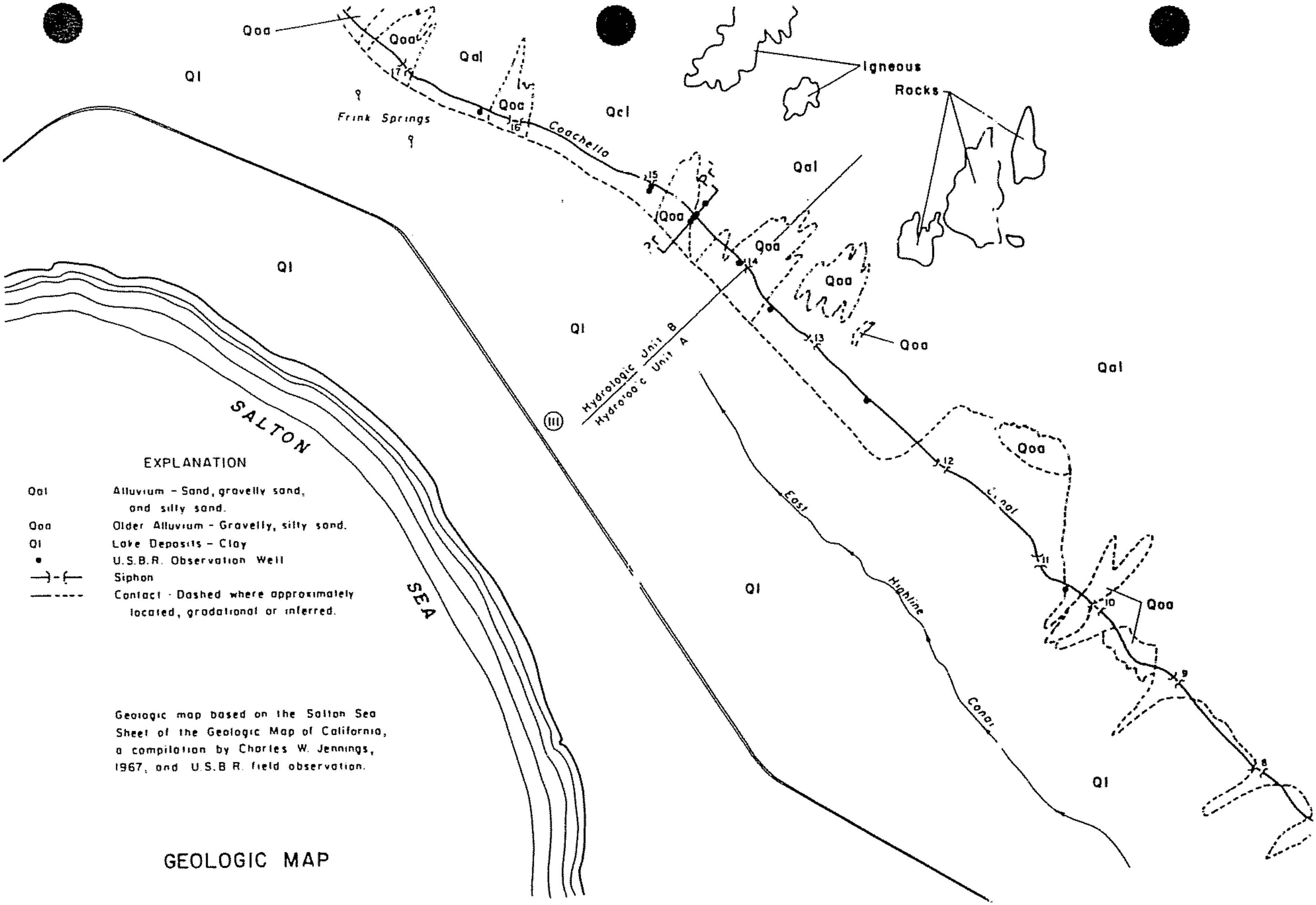
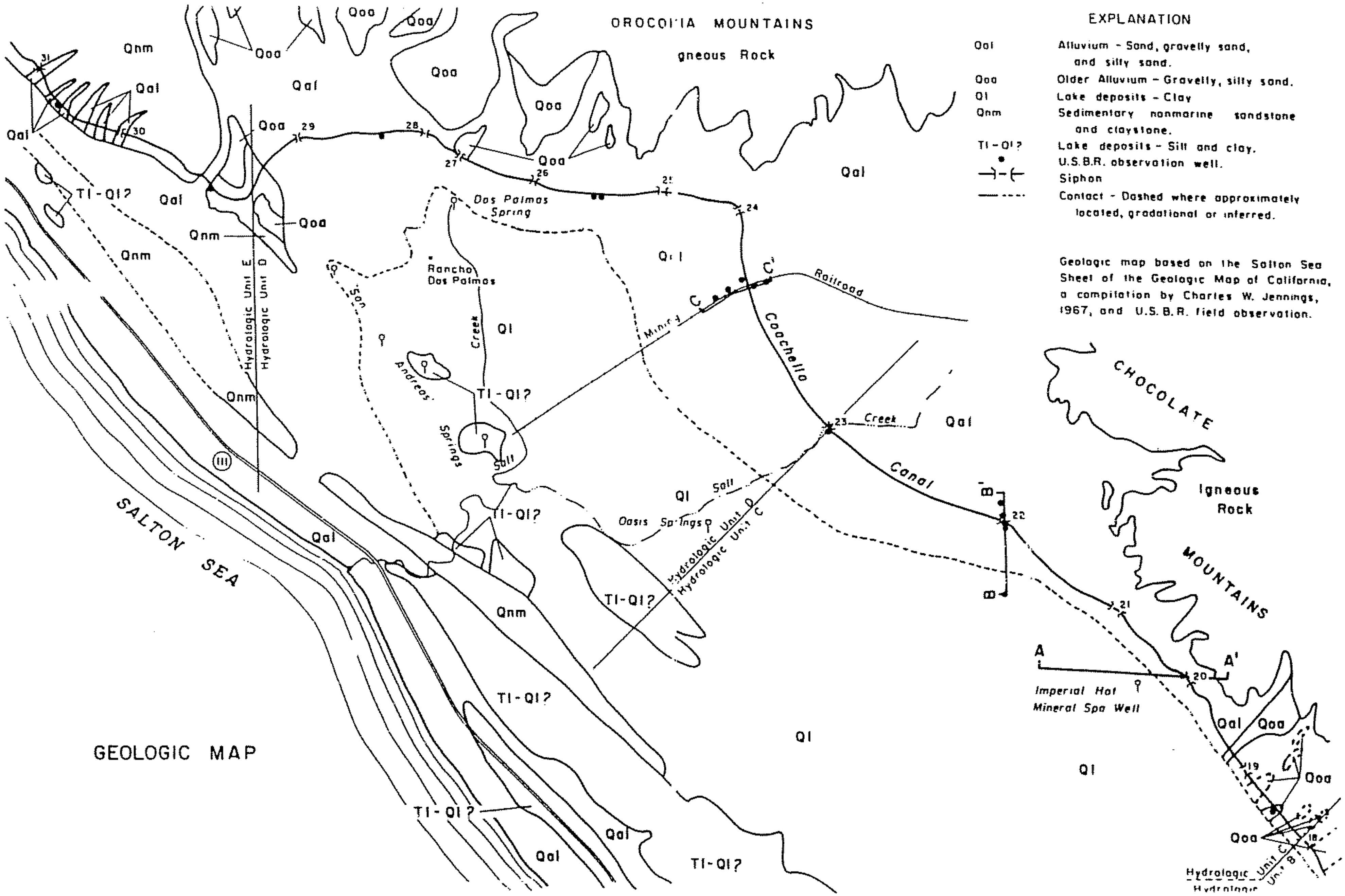


Figure 7. Geologic cross section (C-C') crossing Coachella Canal at railroad crossing upstream of siphon 24.



GEOLOGIC MAP



GEOLOGIC MAP

APPENDIX H RESPONSE TO COMMENTS

APPENDIX H

Salton Sea Authority (SSA) – Response to 20% Deliverable Comments

GENERAL COMMENTS

The following section addresses comments received by Tetra Tech, Inc. from Coachella Valley Water District (CVWD), Imperial Irrigation District (IID), and James Mercer (HSI Geotrans, QA/QC) for the SSA All-American Canal and Coachella Branch seepage study 20% deliverable document. Typographical, syntax, and vocabulary modifications which do not affect the technical content have been incorporated into this (50% deliverable) document without specific response. Specific responses to content and/or structure of the 20% document are outlined below.

SPECIFIC COMMENTS

Coachella Valley Water District

Table of Contents, Section 5:	**"Groundwater Seepage from CB to Salton Sea and Adjacent Wetlands" should read "Groundwater Seepage from CB".**
Response:	The change has been made.
Appendix B.1	**"Linkage between Conceptual and Numerical Model" should read "Description of Numerical Model".**
Response:	The change has been made.
Figure 2-6c:	**The Salt Creek drainage south of Dos Palmas Springs should have two separate channels above the confluence, and they should be dashed to indicate seasonal flow. In addition, the portion of the CB between Siphons 13 and 14 should be shaded per the key to indicate an unlined portion of the canal.**
Response:	The changes have been made to the figure.
Page 2-16, 4th paragraph:	**The paragraph beginning "In 1942, construction..." should be removed from the text.**
Response:	The paragraph has been removed from the text.

Imperial Irrigation District

Page 1-3, 3rd paragraph:	**Something is missing in the second sentence; the first half of the sentence doesn't match the end of the sentence.**
Response:	The sentence has been modified and now reads, "The wetlands mitigation measures proposed in the AAC EIS/EIR and the CB EIS/EIR

will be reviewed based on the quantification of reduced seepage losses to the existing adjacent wetlands."

Page 2-8, 4th paragraph: **IID currently has 10 regulating reservoirs rather than the 6 reservoirs sited by Montgomery Watson (in reference).**

Response: The change has been made to the text.

Figure 2-4: **The basins and boundaries are identified and named with no Imperial Basin shown.**

Response: Figure 2-4 depicts "surface" hydrologic features, wherein the hydrologic areas are identified by the major drainage in that area. The Imperial Valley Basin refers to the corresponding groundwater basin, which is shown on Figure 2-7 with other regional groundwater basins in and around the study area as defined by the California Department of Water Resources.

Page 2-26: **In Section 2.2, Land Use, only the Imperial Basin is described. It would make more sense to describe each basin within the study area that is listed in Figure 2-4, and if the Imperial Basin is described, it should be defined and shown on Figure 2-4.**

Response: In the first sentence of Section 2.2, Imperial "Basin" has been changed to Imperial "Valley" to reflect that what is being referenced is a general geographic region which makes up a considerable portion of the study area, and not a groundwater basin. The groundwater basins shown on Figure 2-7 are described individually in Section 3.1, Definition of Groundwater Basins in the Study Area.

Page 2-26, 4th paragraph: **The first paragraph, second sentence in Section 2.3.1, Surface Water, "...surface water is in general nonpotable." should be changed to "...groundwater is in general nonpotable."**

Response: This section deals specifically with surface water. Section 2.3.2 is specific to groundwater. The second sentence in this paragraph has been modified from "...on the quality of surface water, and surface water is in general nonpotable." to "...on the quality of surface water."

Figure 2-9: **The legend does not appear to be correct.**

Response: The figure title has been changed to "Water District Boundary Map for Study Area", and the CVWD and IID district boundary color designations have been specified in order to clarify the figure.

James Mercer, HSI Geotrans

Page 1-3, 2nd paragraph:	**The first sentence in this paragraph references the features Pilot Knob and Drop 3 on Figure 1-2. These feature locations are not shown on any figure in the report.**
Response:	The locations of Pilot Knob and Drop 3 have been added to Figure 1-2 as well as Figure 2-6b.
Page 2-7, 3rd paragraph:	**The third sentence, "not percolating into subsurface storage eventually draining..." should read "...not percolating into subsurface storage or evaporating eventually draining..."**
Response:	The change has been made.
Page 2-8, 3rd paragraph:	**Show features Drop No. 1 and Siphons 14 and 15 on a map.**
Response:	The features have been included in Figure 2-4.
Page 2-25, 3rd paragraph:	**The recharge estimate of 10,000 acre-feet per year from precipitation (3 inches/year) seems high.**
Response:	The recharge value cited is from U.S.G.S. Professional Paper 486K (Loeltz et al. 1975), page K23, "Recharge also results from infiltration of runoff, mainly in washes and drainageways that discharge to the central part of the valley or to the Salton Sea. This recharge is estimated to average somewhat less than that from the tributary area of San Felipe Creek. Thus, the average annual recharge due to precipitation within the study area probably is somewhat less than 10,000 acre-feet." However, the U.S.G.S. model for the Ocotillo area (Skrivan 1977) cites a recharge rate of 0.02 inches per year over a ½ million acre area of unirrigated land in the Imperial Valley which is approximately 800 acre-feet per year of recharge. The text has been revised to note this discrepancy.

Salton Sea Authority (SSA) – Response to 50% Deliverable Comments

GENERAL COMMENTS

The following section addresses comments received by Tetra Tech, Inc. from Coachella Valley Water District (CVWD), Imperial Irrigation District (IID), the peer review team (Alice Campbell, Ernest Weber, and Dennis Williams), and James Mercer (HSI Geotrans, QA/QC) for the SSA All-American Canal and Coachella Branch seepage study 50% deliverable document. Typographical, syntax, and vocabulary modifications which do not affect the technical content have been incorporated into this (75% deliverable) document without specific response. Specific responses to content and/or structure of the 50% document are outlined below. Where multiple reviewers have submitted the same or similar comment, only one response to the comment has been documented.

SPECIFIC COMMENTS

Coachella Valley Water District

Page 1-1, last sentence:	**"This report is the 20 percent..." should read "This report is the 50 percent...".**
Response:	The correction has been noted, and the "75 percent" document has been appropriately referenced in this sentence.
Page 1-3, 3rd paragraph:	**At the end of the first sentence, remove "...and to those wetlands that would be eliminated by the AAC and CB canal lining projects."**
Response:	This portion of the sentence has been modified to read "...and to existing adjacent wetlands of concern."
Page 5-26, 3rd paragraph:	**The last sentence in the paragraph referencing "wetlands" ...**

Imperial Irrigation District

Page 2-1, 2nd paragraph:	**In the last sentence of the paragraph, the historic recorded low elevation of the modern Salton Sea was –252.2 feet on December 19, 1919. The current elevation of the sea is -225.9 feet.**
Response:	The sentence has been modified, and now reads "The historic recorded low elevation of the modern Salton Sea was 252.2 feet below sea level on December 19, 1919 (IID, personal communication, 1999). The current elevation of the sea (1999) is approximately 226 feet below sea level.
Page 2-8, 3rd paragraph:	**In the second sentence, "1942" should read "1940".**
Response:	The change has been made.

Page 2-8, last paragraph:	**The first sentence should read "...from Drop 3 to Drop 5,..."-there is no drop 6.**
Response:	The change has been made.
Pages 2-9, 2-11, Figure2-3:	**Soils map and information, pages 2-9 and 2-11 – the soils information appears to be incorrect. Neither the map nor Table 2.1 match the USDA-SCS Imperial County Soil Survey. Specifically "CA 606" as shown in Figure 2.3 is Rositas, not Glenbar. "CA603" as shown in Figure 2-3 is Glenbar, not Gadsden. Gadsden soils are not found in the Imperial Valley. In addition, the permeability of Glenber soils ranges from .06-0.2 in/hr, and 0.2-0.6 in/hr, not 6-20 in/hr. The permeability of Rositas soils (fine sands) is 6-20 in/hr. *See Soil Survey of Imperial County California,* USA-SCS, 1980.**
Response:	The soils data currently reflected in the 50% submittal was derived from the State Soil Geographic (STATSGO) data base. Figure 2-3 has been modified to conform to the relevant soil survey published by the Natural Resource Conservation Service (Soil Conservation Service). Table 2-1 containing STATSGO data has been deleted from the 75% submittal.
Page 2-12, 2nd paragraph:	**The third (actually fourth) sentence in the first full paragraph at the top of the page – tile drains in the Imperial Valley are usually 5 to 6 feet deep. A few may be as deep as 7 feet at the outlet end, none are anywhere near 10 feet deep.**
Response:	The sentence has been revised. It now reads "Tile drains are typically at a depth of 5 to 6 feet (a few may be as deep as 7 feet at the outlet end), and carry subsurface water containing dissolved salts to sumps at the tail end of selected fields or discharge directly to drainage canals."
Page 2-19, Figure 2-6b:	**This figure, as well as several others, show the proposed AAC lining project starting at the Colorado River. The proposed AAC lining begins one mile west of Pilot Knob, as noted on page 3-1 (actually page 1-3).**
Response:	Figures 1-2 and 2-6b have been modified to indicate the proposed AAC lining beginning one mile west of Pilot Knob, as noted on page 1-3.
Page 2-23, 1st paragraph:	**The first paragraph is incomprehensible. Looks like something got edited out that should have been left in.**
Response:	The second sentence in the first paragraph has been removed, as it was more specific to groundwater recharge and Colorado River channel oscillations rather than historic development of the canal system. The first sentence in this paragraph "By 1900, over one thousand people..." is now part of the next paragraph, and should make more sense now.
Page 2-28, 1st paragraph:	**The New River derives roughly 65% of its flow from irrigation return flows in the Imperial Valley, with the remaining 35%**

(175KAF out of 491KAF) of water flowing from Mexico at the International Boundary.

Response: The sentence has been modified to reflect these quantities.

Page 2-7, 4th paragraph: **The discussion of the New and Alamo Rivers as large agricultural drainage channels needs to be included or they should be located under the heading "Canals and Drains" on page 2-8.**

Response: The referenced paragraph indicates that the New and Alamo Rivers "intercept post irrigation seepage collected along an elaborate subdrain tile system." The Rivers are an integral part of the drainage system and essentially serve as large agricultural drainage channels. However, the Rivers are a natural drainage feature of the valley which were "considerably widened and deepened between 1904 and 1907, when the bulk of Colorado River water was entering Imperial Valley...". One could argue that without the Colorado River flooding during this period, the channels may not exist in their current morphology. However, the channels were natural depressions which were simply further incised by the flooding. Although some modifications have been made to enhance their ability to capture agricultural runoff, to include the New and Alamo Rivers as part of the "Canals and Drains" section infers that they are engineered structures, which is not the case.

PEER REVIEW TEAM

Alice Campbell

General: **Add San Andreas and Imperial Faults to all water level contour maps in order to see the relationship between possible fault barrier effects and water level contours/groundwater flow direction.**

Response: The primary fault lineations within the study area have been superimposed on the groundwater contour maps. In addition, the faults have been included on aerial photograph and satellite imagery figures.

Figure 2-2: **The geology map uses antiquated terminology, does not reference the source, does not show the shoreline of ancient Lake Cahuilla, etc.**

Response: The geology map has been reconstructed, using California Division of Mines and Geology Santa Ana, Salton Sea, and San Diego-El Centro map sheets in a composite with accompanying map symbols.

Page 2-23, Section 2.1.5: **This section needs to tie geology to model assumptions explicitly.**

Response: Text has been added to the section in order to clarify which hydrostratigraphic units correspond to layers 1, 2, and 3 in the model, and their relative positions in the geologic column.

Ernie Weber

General:	**The majority of comments submitted by Mr. Weber generally coincided with Ms. Campbells' comments and other comments which have previously been addressed.**
Figure 2-8:	**The land use map appears incomplete, illustrating land use for the south Coachella Valley, and none for the Central Imperial Valley.**
Response:	The map was obtained from the University of Redlands database, and has not been completed to date. This particular figure has been eliminated, and text in the "land use" section of the report now refers to Figure 2-6a as a general reference, which clearly illustrates the predominantly agricultural land use in the study area.
Table 2-1:	**The permeability values assigned for individual soil classifications in this table are inconsistent with the drainage classifications.**
Response:	The soils data currently reflected in the 50% submittal was derived from the State Soil Geographic (STATSGO) database Figure 2-3 has been modified to conform to the relevant soil survey published by the Natural Resource Conservation Service (Soil Conservation Service). Table 2-1 containing STATSGO data, has been deleted from the 75% submittal.

Dennis Williams

Page 1-5, Figure 1-2:	**Show Siphons 7 and 32**
Response:	Siphons 7 and 32 have been labeled on Figure 1-2.
Page 2-1, 2nd paragraph:	**The first sentence of the paragraph "...to the north-northwest by the Orocopia and Chocolate Mountains,..." should read "...to the north-northeast...".**
Response:	The correction has been made.
Page 2-8, 5th paragraph:	**"...at the final connection to the West Side Main Canal...", the "West Side Main Canal" was named as "Westside Main Canal" in other places.**
Response:	A universal change has been made to the document, and the correct designation is "Westside Main Canal".
Page 2-9, Figure 2-3:	**The Westside Main Canal was mislabeled as "West Main Canal".**
Response:	The label has been corrected and now reads "Westside Main Canal".
Page 2-28, 5th paragraph:	**In the second sentence of the paragraph "...water is delivered annually to over 500,00 acres of agricultural land.", should be "...over 500,000 acres...".**

<u>Response:</u>	The correction has been made.
<u>Page 3-1, 3rd paragraph:</u>	**The fourth sentence of the paragraph reads "Natural recharge to the basin has been estimated to be 1,200 acre-feet per year." Natural recharge to the Coachella Basin has been estimated to be 80,000 acre-ft per year by the cited reference (Department of Water Resources, 1975).**
<u>Response:</u>	The quantity cited was an estimate of natural recharge for that portion of the Coachella Basin represented by the 13 square miles within the study area. This was unclear in the text, and in reality, natural recharge does not occur uniformly across the aerial extent of any basin. The reference has been changed to reflect the natural recharge to the basin as a whole, according to the cited reference.
<u>Page 3-2, 7th paragraph:</u>	**"...the San Andreas Fault in the region since the middle Eocene (Crowell and Susuki, 1959)". The cited reference is not listed in the Section 10 Bibliography.**
<u>Response:</u>	The reference has been added to the bibliography.
<u>Page 3-4, 2nd paragraph:</u>	**"... and 1960 for the East Mesa (Olmstead et al. 1973...". The cited reference is not listed in the Section 10 Bibliography.**
<u>Response:</u>	The reference has been added to the bibliography.
<u>Page 3-5. Figure 3-1:</u>	**East Mesa should be labeled. Faults should be added in this figure to show groundwater barrier effect.**
<u>Response:</u>	The revisions have been made.
<u>Page 3-7, 3rd paragraph:</u>	**"This feature is attributed to a groundwater barrier that occurs in this area, which appears to be associated with the Elsinore Fault. Note that despite the presence of faults in eastern Imperial Valley such as the Algodones Fault, the groundwater table does not appear to reflect a barrier effect in the eastern study area." The Elsinore and Algodones Faults were not discussed in Section 3.2.1 "Stratigraphy and Structure" and were not shown in Figure 2-2 "General Geologic Features of Study Area".**
<u>Response:</u>	The Elsinore Fault is outside of the study area. This section of the report was written prior to establishing the final boundaries of the model area, and this particular paragraph has been deleted. The following text has been included in the previous paragraph; "Despite the presence of the San Andreas and Algodones Faults in the East Mesa area, the groundwater contours do not necessarily appear to create a barrier effect. Mounding effects may also be directly attributable to canal seepage or a combination of the two. The Algodones Fault is an unmarked dotted line northeast of the San Andreas Fault on Figure 2-2a.

Page 3-7, 4th paragraph: **"Groundwater levels in the study area have varied significantly over time...", however, the next paragraph "In general, the water table in the central Imperial Valley has not changed significantly". Please specify the areas having significant groundwater level variations.**

Response: The first sentence of the paragraph has been modified, and now reads "Groundwater levels adjacent to the canals in the East Mesa area have varied significantly over time, primarily in response to seepage of imported Colorado River water."

Page 3-8, 2nd paragraph: **"The 1992 period was chosen..." should be "1993".**

Response: The change has been made.

Figures 3-4 and 3-5: **Label aquifers and aquitards.**

Response: The designations have been added in the figure legend.

Page 3-21, 4th paragraph: **"...and a deeper confined alluvial aquifer that is bounded above by the aquitard...". Aquitard implies a "leaky" aquifer so that the deeper confined aquifer is actually "semi-confined".**

Response: The sentence now reads "semi-confined"

Page 4-2, 2nd paragraph: **"The 70 percent decline in seepage from this upper gauge-defined reach...". The "upper" should be "lower".**

Response: The change has been made.

Page 4-16, 2nd paragraph: **"From 1942 to 1998, seepage from the AAC...(Bureau of Reclamation 1991)". The 1998 is later than the 1991 cited reference.**

Response: The sentence has been corrected, and now reads "From 1948 to 1988,..."

Page 4-33, 3rd paragraph: **"The AAC EIS/EIR presented a similar estimate of 90 percent of the total AAC seepage, or 95,850 af/yr, for the AAC seepage that flows into East Mesa." The "East Mesa" should be "Mexicali Valley".**

Response: The change has been made.

Page 5-1, 4th paragraph: **"The decline from the initial seepage rate of the upper gauge-defined reach...". The "upper gauge-defined reach" should be "section below check 6A".**

Response: The change has been made.

James Mercer, HSI Geotrans

Page 4-34, 1st paragraph:	**Add a last sentence to this paragraph; "The groundwater model will be used to refine this estimate."**
Response:	The sentence has been added to the text.
Page 4-33, 1st paragraph:	**Onto the last sentence, add "...without using a groundwater model."**
Response:	The addition has been made.
Figure 4-1:	**What about the last 10 years of data from 1989-1999?**
Response:	The last 10 years of data for the upper gauged reach have only recently been acquired from IID, and have been added to the figure. The lower gauged reach data is unavailable for 1989-1999.
Page 3-28,Table 3-2:	**The "af/yr" designation has also been used but not defined in Table 3-1 (as acre-feet per year).**
Response:	The defining footnote has been added to Table 3-1.
Page 3-22, 1st paragraph:	**What about drainage to the wetlands that are part of this study?**
Response:	The last sentence of the paragraph has been modified, and now reads, "....and discharge into the Salton Sea and adjacent wetlands."
Page 3-18, 3rd paragraph:	**In the 2nd sentence, an effective porosity of 15 percent is cited, which is relatively low for sands and gravels. Specific yields (essentially effective porosity for sands and gravels) used later are 20 to 25 percent.**
Response:	The effective porosity used to calculate groundwater velocity has been changed to 20 percent, with a resultant estimated groundwater velocity of 450 feet per year for the East Mesa area.

Salton Sea Authority (SSA) – Response to 75% Deliverable Comments

GENERAL COMMENTS

The following section addresses comments received by Tetra Tech, Inc. from Coachella Valley Water District (CVWD), Imperial Irrigation District (IID), and James Mercer (HSI Geotrans, QA/QC) for the SSA All-American Canal and Coachella Branch seepage study 75% deliverable document. The peer review team (Alice Campbell, Ernie Weber, and Dennis Williams) has submitted a final report dated 12 June, 1999, which, in addition to our responses, make up Appendix D of this document. Typographical, syntax, and vocabulary modifications which do not affect the technical content have been incorporated into this (90% deliverable) document without specific response. Specific responses to content and/or structure of the 75% document are outlined below. Where multiple reviewers have submitted the same or similar comment, only one response to the comment has been documented.

SPECIFIC COMMENTS

Coachella Valley Water District

<u>Page E-2, 1st paragraph:</u>	**At the end of the paragraph, add the sentences "Wetlands are dominated by an invasive exotic phreatophyte – salt cedar. Salt cedar has taken over approximately 50 percent of total wetland acreage along the AAC and 70 percent along the CB.".**
<u>Response:</u>	The sentences have been added to the text with the appropriate references for the values cited (Bureau of Reclamation 1993, 1994).
<u>Page E-3, 2nd paragraph:</u>	**Add the sentence "The approach in mitigation was one of exchange and replacement of the invasive, low value salt cedar habitat for higher value screwbean mesquite, honey mesquite, and other native habitat.".**
<u>Response:</u>	The sentence has been added to the text.
<u>Page E-3, 3rd paragraph:</u>	**Add the following text: "The Model predicts much lower reductions in seepage in the CB lining project than originally projected in the draft CB EIR. Original EIR documentation projected immediate (within 10 years) reductions in evapotranspiration resulting in losses of 4,293 acres of wetlands. Of that 3,420 acres, 80 percent of the acreage would consist of pure stands of salt cedar. To mitigate for these losses, the Draft EIR called for revegetation with native vegetation such as California fan palms, honey mesquite, screwbean mesquite, cottonwood/willow, and riparian shrubs; acquisition of riparian and marsh communities; and maintenance of flows in Salt Creek (up to 7,000 acre-feet was reserved, as needed, to provide for mitigation.). When modeled, these mitigation commitments result in surface and evapotranspiration demands lower than current natural groundwater discharges. Recognizing that surface water will be a part of mitigation for lining the CB, model studies indicate that**

natural discharges from groundwater storage will be sufficient to sustain proposed mitigation measures well beyond 2026.".

Response: The text has been added.

Page 2-18, 5th paragraph: **After the first sentence, add the following two sentences; "These wetlands are dominated by an invasive exotic phreatophyte: salt cedar. Salt cedar has taken over approximately 50% of total wetland acreage."**

Response: The sentences have been added to the text.

Page 2-19, 2nd paragraph: **After the second sentence, add the sentence "Salt cedar has taken over approximately 70% of total wetland acreage."**

Response: The sentence has been added to the text.

Page 3-4, 3rd paragraph: **The fifth sentence should read "Prior to construction of the AAC and CB, groundwater contours were influenced by the Alamo Canal and showed only a westward gradient (see Figure 4-3).**

Response: The sentence has been modified and now reads "Prior to construction of the AAC and CB, groundwater contours in the region were influenced by the Alamo Canal and exhibited a generally westward gradient (see Figure 4-3).

Page 5-2, 1st paragraph: **The third sentence "...unknown because it occurred prior to the Coachella Branch lining in 1980." should be modified to read "...probably the result of the removal of the original bentonite liner concurrently with intensive aquatic weed removal efforts in the 1970's and 1980's. Prior to the construction of the parshall flumes, during the lining of the first 49 miles, the measurement of seepage loss in the middle section was uncertain."**

Response: The sentence has been modified as stated.

Page 5-5, Table 5-1: **Under the table footnotes, add "Total Wetlands consist of 70% Salt Cedar".**

Response: The footnote addition has been made.

Page 5-16, Section 5.2.4: **Add the text "Wetlands are dominated by an invasive exotic phreatophyte: salt cedar. Salt cedar coverage has expanded at the expense of native vegetation and has taken over approximately 70% of total wetland acreage. Under the draft EIR, canal lining mitigation for loss of riparian vegetation shall be accomplished through revegetation (California fan palms, honey mesquite, screwbean mesquite, cottonwood, willow, and riparian shrubs), acquisition of riparian/marsh communities, and maintenance of flows in Salt Creek."**

Response:	The text has been added.
Page 5-22, 3rd paragraph:	**In the third sentence, add the text "...(ignoring displacement by salt cedar)..."**
Response:	The text "...(disregarding propagation of salt cedar)..." has been added.
Page 5-24, Section 5.3.6:	**The last sentence "...lined, but mitigation is not proposed because the current users do not have established groundwater rights for CB canal seepage water." should read "...lined. CVWD maintains a domestic water system in the Hot Mineral Spa area and will provide domestic service at standard rates in accordance with current District ordinances."**
Response:	The sentence has been modified as stated.
Page 7-6, 1st paragraph:	**Add the following sentence to the end of the paragraph: "For comparison, the Draft EIR mitigates for a 75 percent drop in the CB wetlands within 10 years."**
Response:	The text has been added.
Page 8-7, section 8.4.1:	**Add the following text to the end of the section: "Specifically, the mitigation commitments take into account current wetlands which are dominated by an invasive exotic phreatophyte: salt cedar. Salt cedar has taken over approximately 50% of total wetland acreage in the AAC and 70% for CB. Mitigation measures include the replacement of the poorer quality desert riparian wetlands with higher quality native marsh, honey mesquite, and screwbean mesquite.**
Response:	The text has been added.

Imperial Irrigation District

Comments received from IID were generally editorial in nature, or had already been addressed by other reviewers. The majority of the comments were specific to additional text for table clarification. In general, text modifications made subsequent to the 75% deliverable which did not affect the technical content of the document were reviewed by IID and were acceptable.

James Mercer, HSI Geotrans

Page 6-2, 3rd paragraph:	**At the end of the paragraph, add the sentence "The MODFLOW code has been well tested and is widely accepted by the technical community.".**
Response:	The sentence has been added to the paragraph.

Page 6-13, 1st paragraph: **The Hsieh and Freckleton (1993) reference is not in the bibliography.**

Response: The reference has been added to the bibliography.